EARTH
SCIENCES
LIBRARY

BERKELEY
LIBRARY
UNIVERSITY OF
CALIFORNIA

EART

53238345

QE 475
A2V36
1904
V. 2
EART

CHAPTER VI.

THE BELT OF WEATHERING.

In Chapter IV general statements were made as to the nature of the alterations of the belt of weathering and the relations of these to alterations in the belt of cementation and the zone of anamorphism. The statements were mainly from the physical-chemical point of view, and no attempt was made to give in detail the facts upon which they were based. It is the purpose of the present chapter, first, to consider fully the phenomena of the belt of weathering from a geological point of view, and, second, to interpret these phenomena in terms of the physical-chemical principles which have been developed in the previous chapters. However, the two are not separately considered, but are interwoven.

BELT OF WEATHERING DEFINED.

The belt of weathering has been shown to be a part of the zone of katamorphism. (See Chapter IV.) From a physical-chemical point of view this belt is one in which the reactions take place with liberation of heat, and with expansion of volume provided all the compounds formed remain in situ.

At a variable depth below the surface of the earth ground water is a connected body which fills all of the openings. The position of the surface of this body of water may be called the level of ground water. Above the level of ground water the openings are ordinarily not filled with water. From a geological point of view the belt of weathering is the surficial belt extending from the surface of the earth to the level of ground water. The thickness of this belt varies greatly. At or near streams, lake, or ocean, and in areas where the surface is not much higher than the adjacent bodies of water, the level of ground water may reach near or to the surface, and thus there be for these areas either a very thin upper belt or even none. In regions of average precipitation, moderate elevation, and moderate irregularities of topography the level of ground water is usually from 3 to 30

meters from the surface. It is especially likely to be near the surface in regions where there is abundant precipitation and a thick layer of drift or a thick layer of disintegrated rocks. In elevated and irregular regions, especially those in which the precipitation is rather small, the level of ground water is frequently 30 to 90 meters below the surface, and in high desert regions the level of ground water may be 300 or more meters below the surface.

The above general statements may be illustrated by various regions of the United States. In the humid regions of eastern United States the level of ground water varies from 0 to 27 or 30 meters below the surface. Throughout the greater part of the drift-covered region the sea of ground water is penetrated at a depth of less than 15 meters, although on the higher drift hills the level of ground water may be from 15 to 30 meters

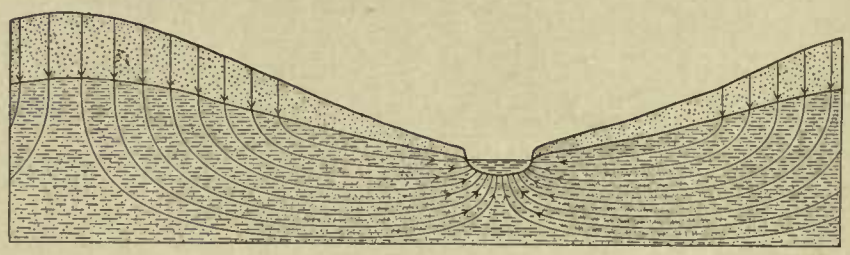


FIG. 5.—Relations of level of ground water to topography and to surface drainage. Lines with arrows are lines of flow. After King.

below the surface. For the disintegrated regions of the southern Appalachians, water is generally reached at a depth of less than 30 meters. For the greater part of the Coastal and Gulf plains water is ordinarily found at a depth of less than 15 meters. In the high limestone region of Kentucky and Tennessee the level of ground water may be 60 to 90 meters below the surface. For the major portion of the western part of the great plateaus east of the Cordilleras the level of ground water is from 30 to 75 meters below the surface, although adjacent to the streams it is less than this.[a] In the arid regions cut by deep canyons the level of ground water may be far below the surface. In portions of such regions it is so deep that some authors have concluded that water wholly fails. But that this is not so is shown by the numerous springs which issue in these regions along the

[a] Darton, N. H., Preliminary report on the geology and water resources of Nebraska west of the one hundred and third meridian: Nineteenth Ann. Rept. U. S. Geol. Survey, pt. 4, 1899, pl. cx.

streams at the base of the canyons. For instance, in the Grand Canyon of the Colorado many springs issue near the river and along the side canyons. Some of these are large and are loaded with calcium carbonate.[a] The rule is here, as elsewhere, that the level of ground water starts at the level of the river and rises toward the divide. But in this arid western country, dissected by deep, steep canyons and broken by innumerable fractures, the level of ground water in some places is as much as 1,000 meters or more below the surface.

While there is great variation in the depth of the level of ground water, and ground water is found only at a considerable depth in many regions, on the average the depth of ground water in the United States is not great—probably in the neighborhood of 30 to 50 meters.

FORM OF LEVEL OF GROUND WATER.

From the foregoing it follows that the form and position of the level of ground water are largely dependent upon the topography, upon the character of the openings in the rocks, upon the precipitation, and upon other factors. In general, the more accentuated the topography the greater is the difference between the elevation of the surface and the level of ground water. Where from a lowland a steep ridge rises, the level of ground water also rises, but less rapidly and with considerable deviation between the two. Where from a lowland there is a gentle rise, the level of ground water also rises gently, and it more nearly corresponds with the surface than in the case of an abrupt rise. The position of the level of ground water is largely dependent upon precipitation. In humid regions it is apt to be near the surface; in arid regions it is farther from the surface.

The relations of the level of ground water to topography and to surface drainage are illustrated by fig. 5.[b] Where the openings in the rocks are numerous and large, there are much greater differences between the surface and the level of ground water than where the openings are few and small. For this there are two reasons: First, the precipitation in a region of large openings more readily makes it way through the openings to the drainage level than in a region where the openings are small, for resistance to movement increases as the openings become small, and therefore on

[a] Powell, J. W., Explorations of the Colorado River of the West, 1875, p. 94.

[b] King, F. H., Principles and conditions of the movement of ground water: Nineteenth Ann. Rept. U. S. Geol. Survey, pt. 2, 1899, p. 99.

account of the slow movement a greater head is necessary in order that equilibrium shall obtain in the sea of ground water between additions from precipitation and subtractions by flowage. Second, the level of the ground water is also dependent upon capillarity. The effect of capillarity is to raise the water surface in the small openings of the rocks above its natural level as found in wells. The amount of this rise is inversely as the diameter of the openings This amount, as shown on page 151, varies from nothing in the largest capillary tubes to 166 meters in circular tubes of limited size between capillary and subcapillary openings, and to 83 meters in similar sheet openings. In circular capillary openings between 1 mm. and 0.001 mm. in diameter the rise varies from 3.32 cm. to 33.2 meters, and in similar sheet openings one-half of this amount. A comparison of the above numbers shows that in openings limiting those of capillary and subcapillary size the rise is five times these larger amounts. When it is remembered that in large classes of sediments, such as fine sands and clays, the openings approach subcapillary size, or even are of subcapillary size, it is evident that the amount which the level of ground water may be raised as a result of capillarity may be a very important factor in determining its position.

While the level of ground water in rocks in which the openings are capillary or subcapillary may be greatly affected by capillarity, in the supercapillary and larger capillary openings this is not an appreciable factor. It follows that there may be great changes in the level of ground water in passing from places where the openings are supercapillary to where they are capillary, and from places where the openings are capillary to where they are subcapillary.

Illustrations of these principles are found in all countries. In fractured limestone regions containing caves the level of ground water may follow approximately that of the drainage of the district, and thus there be a great difference between the topography of the surface and that of the ground-water level. Where a region is covered with a thick mantle of fine material, as drift, the topography of the ground water may very closely follow that of the surface. A good illustration of an open limestone area is furnished by the Grand Canyon region of Colorado. In this district the topography is much accentuated and the rocks are largely limestone, commonly much

fractured, and there is therefore great difference between the topography of the surface and that of the level of ground water. In contrast with this may be mentioned the drift-covered regions of North America. Here, even where the topography is only moderately accentuated, the level of ground water may rise rather rapidly. This is illustrated by the rise of that level where one passes from one of the numerous lakes of the region to the adjacent higher lands. A good instance is found at Madison, Wis. About 360 meters from Lake Mendota and 25 meters above its surface, on the slope of a hill, is a well in which the water is, on the average, about 15 meters above the surface of the lake.[a]

AMOUNT AND SOURCE OF WATER IN BELT OF WEATHERING.

Under ordinary circumstances the water above the level of ground water is mainly that of imbibition. (See p. 124.) This water is held by the adhesion between the mineral particles and the water. But in the arid regions a large part of the belt of weathering may not contain more than a fraction of the water of imbibition. Whitney explains that not only the surface soil but strata below the soil are often so dry as to be dusty.[b]

However, in contrast with this, for many regions, and for much of the year, the water present is greater than that of imbibition and consequently includes water of hygrometricity. (See p. 124.) Indeed, locally, and for a time, the belt may be nearly or quite saturated with water. The upper belt is therefore characterized by conditions ranging from almost complete dryness, through water of imbibition, to almost complete saturation.

It has been shown in Chapter III that the circulating ground water is almost wholly derived from precipitation, although it is possible that a small fraction of this water is derived from deep within the earth. Before considering the circulation in the belt of weathering, it is necessary to understand how the precipitation is divided among the surface water, the belt of weathering, and the belt of cementation.

In the greater part of the very humid region comprising the southeastern United States the rainfall varies from 100 to 150 cm., but runs up to 175 cm. In this region, according to Newell, the run-off in streams is

---

[a] King, F. H., cit., p. 99.

[b] Whitney, Milton, Conditions in soils of the arid region: Yearbook of the Dept. of Agric., 1894, pp. 159–160.

about 50 per cent of the total precipitation.[a] In the humid region of the United States comprising the Great Lakes region and a broad belt extending through to central Texas the rainfall varies from 50 to 100 cm. The run-off in this region varies from 12 cm. to nearly 50 cm., or from 25 to 47 per cent, the smaller percentages of run-off corresponding to the lesser rainfalls. In the semiarid portion of the Cordilleran region, where the rainfall is 25 to 50 cm., the run-off varies from 5 to 12 cm., or is from 20 to 25 per cent of the precipitation. In the arid regions, where the precipitation is 25 cm. or less, the run-off varies from 0 to 5 cm., or from 0 to 20 per cent. Thus, according to Newell, the water flowing in the streams varies from 50 per cent or more of the precipitation in the most humid regions of the United States to 1 or 2 per cent in the most arid regions.[b]

All these cases fall under the general rule given by Powell, "that the coefficient of run-off increases with the rainfall;"[c] and it may be stated generally "that in humid countries the percentage of run-off to rainfall is larger than in the arid regions; and, of several localities, that one having the greatest mean annual rainfall will, cæteris paribus, have a run-off disproportionally large to the others."[d] However, as pointed out by Powell, it does not follow from this that the annual run-off of any one basin is directly proportional to the measured annual rainfall, for there are many factors entering into the run-off besides the amount of the precipitation. Some of these factors are the distribution of precipitation during the year, the temperature and other climatic conditions, the topography, the chemical and physical character of the soil, cultivation, vegetation, etc. Of these secondary factors that of topography is very important. In proportion as the declivities are steep the run-off is likely to be large; in proportion as the slopes are gentle the run-off is likely to be small. It follows from this that the relative run-off is less in large drainage basins than in small ones, because the large drainage basins are apt to have a greater percentage of level land.[e]

---

[a] Newell, F. H., Results of stream measurements: Fourteenth Ann. Rept. U. S. Geol. Survey, pt. 2, 1894, pp. 149–154, pls. v and vi.

[b] Newell, F. H., Irrigation in the United States, Crowell & Co., New York, 1902, p. 27.

[c] Powell, J. W., Second annual report of the irrigation survey: Eleventh Ann. Rept. U. S. Geol. Survey, pt. 2, 1891, p. 27.

[d] Powell, cit., p. 27.

[e] Newell, F. H., Water supply for irrigation: Thirteenth Ann. Rept. U. S. Geol. Survey, pt. 3, 1893, pp. 13–14.

This rule is well illustrated by the arid and semiarid regions, where a very large portion of the run-off is that of the precipitation of the mountain regions. Whitney estimates that in the level districts of the arid region of the United States, even where the rainfall is as high as 50 cm., only 10 per cent, or 5 cm., of the rainfall passes into the run-off.[a]

The cultivation of the soil is another of the secondary factors which has an important influence in the amount of run-off. Proper soil cultivation produces a rough surface having many minor depressions arranged in such a way as to have the channels follow the contours. Also, cultivation produces numerous large openings in the upper 5 to 30 cm. of the soil. As a result, when precipitation comes the depressions hold the water. From these depressions it makes its way easily into the large openings. The big openings give a large surface from which the water can make its way into the smaller openings of the soil. Therefore, in cultivated soil a much larger portion of the water makes its way into the soil than under natural conditions. The run-off is greatly decreased and the water for circulation in the belt of weathering is greatly increased.

It will be seen later, in considering the belt of cementation, that the run-off includes both the water which never goes below the surface of the ground and that which issues from the belt of cementation. Much the larger part of the water of the belt of cementation passes through the belt of weathering on its way to the belt of cementation. All of the water not included in the run-off has its entire circulation in the belt of weathering. In the United States it follows, from the figures above given, that the entire circulation of about 50 per cent of the precipitation in the more humid regions is confined to the belt of weathering. In the less humid regions from 53 to 75 per cent is confined to this belt. In the semiarid regions from 75 to 90 per cent is confined to this belt. In the arid regions from 90 to 100 per cent of the precipitation has its only ground circulation in the belt of weathering. It is therefore clear that the proportion of the water of precipitation concerned in the circulation of the belt of weathering is much greater than that concerned in the circulation of the belt of cementation; for the belt of weathering has exclusive control of from 50 to 100 per cent of the total precipitation, and nearly all of the water of the belt of cementation first circulates in the belt of weathering.

---

[a] Whitney, Milton, Conditions in soils of the arid region: Yearbook of the Dept. of Agric., 1894, pp. 157–159.

However, it does not follow that the water present in the belt of weathering at any one time is as great as the amount in the belt of cementation. Indeed, the amount of water in the belt of weathering is only a small fraction of that in the belt of cementation. The explanation of this is that the water contributed to the belt of weathering remains in the belt only a short time—a few minutes, a few hours, a few days, or possibly a few years; while much of the water of the belt of cementation remains in that belt for many years. In the case of the deeper and longer circulations of the latter belt, as shown on pages 585–586, much of the water must have remained underground for centuries. Therefore, while a much larger percentage of the water of precipitation takes part in the circulation of the belt of weathering than in the belt of cementation, at any given time the amount of water at work in this belt is much less than that in the belt of cementation.

THE CIRCULATION.

It has already been seen (pp. 146–152) that the chief factors which control the movement of the water in the belt of weathering are (1) gravity, (2) mechanical movement, (3) molecular attraction, and (4) plant roots. The special action of these factors in the belt of weathering needs consideration.

The force of gravity is vertical and downward, and therefore, so far as this force is concerned, there is a continual tendency for water to be drawn from above the surface of the ground into and directly through the belt of weathering to the belt of cementation. Where the different parts of the water interfere, as they do in the belt of cementation, there may be superimposed on this vertical movement very important lateral movements, as seen on pages 572–576. But the interference due to hydrostatic pressure comes only when the rocks are saturated. In general the rocks of the belt of weathering are not saturated; and hence the lateral movements in this belt due directly to gravity are unimportant, except locally and for short periods of time.

In the belt of weathering the effect of mechanical movement controlled by gravity is to steadily make the soils more compact, and thus to decrease the size of the openings and so to promote capillary action. Also, to some extent, mechanical consolidation tends to squeeze out the moisture and so to force it to the surface or to the belt of cementation.

The influence of molecular attraction is to draw the water from areas of more moisture to areas of less moisture. Since the water falls upon the surface, the first tendency of this force is, like that of gravity, to draw the water from the surface into the soil and downward. However, there are many modifications of this general tendency. Immediately after precipitation molecular attraction works very effectively with gravity in carrying the water downward, but after rainfall has ceased, evaporation near the surface very frequently results in the surface soil containing less moisture than the subsoil or the deeper parts of the belt of weathering. Under these circumstances the force of molecular attraction draws the water from below the surface toward the surface, in opposition to gravity. Also, whenever the belt of weathering is somewhat deficient in moisture, molecular attraction tends to draw water from below the level of ground water into the belt of weathering. These movements are either upward or downward; but whenever local conditions produce lateral variations in moisture, molecular attraction tends to give the water a horizontal component from places of more moisture to places of less moisture.

Wherever roots are present they absorb water from the immediately adjacent soils, and carry it surfaceward. The roots extend both vertically and laterally, and hence the movement of water due to roots is both lateral and vertical. Where roots are present, on account of the absorption of water the soil adjacent to the roots is deficient in amount. As soon as this deficiency appears the force of molecular attraction carries the water from places of more moisture to those places of less moisture, and thus replenishes the supply.

The downward and upward movements of water controlled by the above forces are of such consequence that they are entitled to separate consideration.

DOWNWARD MOVEMENTS OF WATER.

As has been seen, the general forces producing downward movement of water are gravity and molecular attraction; with these forces mechanical movement may cooperate. The results which these forces accomplish are very different under different circumstances. Some of the most important of the variable circumstances affecting the downward movement of water are the irregularities in precipitation and the amount of water in the soil and subsoil.

If precipitation comes suddenly and abundantly an upper layer of the soil may become saturated, and this layer be separated from the belt of saturation below by a layer in which the pore spaces are largely occupied by air. The air below the surface layer of saturation prevents the ready passage of the water downward, and if precipitation continues a large part of the falling water may be prevented by the air from easily making its way into the soil, and consequently joins the run-off. But, as explained later, where the soil is cultivated deeply, so as to leave a considerable percentage of large openings near the surface, and from this supply a temporary reservoir is furnished, a considerably larger proportion of the precipitation may get into the ground than in uncultivated areas.

The water in an upper saturated layer may make its way downward in two ways, (1) the confined air below slowly escapes, either by upward creep or through the rare larger passages which are not filled with water, and the water consequently moves downward; and (2) if the soil particles below the layer of saturation are moistened or contain water of imbibition, the water driven by gravity and capillarity slowly creeps downward along the surfaces of the particles.

If, however, the particles below the upper layer of saturation be entirely dry, this condition exerts a strong retarding influence. Says Whitney: "Water does not readily spread through a previously dry soil, because the tension or contracting power of the surface of the water is greater than the attraction of the soil grains, which tends to cause its diffusion through the mass. One may see, therefore, a nearly saturated layer closely adjacent to a perfectly dry and dusty mass."[a] The explanation of this retardation is expressed differently by Wolff, who attributes it to the elastic meniscus at the front of the moving water.[b] (See p. 141.)

The above condition of affairs is especially likely to occur in the arid and semiarid regions, where a large part of the belt of weathering is very dry. According to Whitney, even where the annual rainfall is as much as 50 cm., nearly the entire amount may remain within a few meters of the

[a] Whitney, Milton, Conditions in soils of the arid region: Yearbook of the Dept. of Agric., 1894, p. 160. King, F. H., Principles and conditions of the movement of ground water: Nineteenth Ann. Rept. U. S. Geol. Survey, pt. 2, 1899, p. 93. Merrill, George P., Rocks, rock-weathering, and soils, Macmillan Co., New York, 1897, pp. 379–380.

[b] Wolff, H. C., The unsteady motion of viscous liquids: Trans. Wisconsin Acad. Sci., Arts, and Letters, vol. 12, pt. 2, 1900, pp. 552–553.

surface, and separated from the belt of cementation by a belt of dry soil. This holding of the water of precipitation near the surface, according to Whitney, explains the greater efficiency of water in the production of crops in the semiarid regions than in the humid regions.[a]

In opposition to the above, where the subsoil is moist and where the rate of precipitation is moderate, the water may make its way downward, drawn by gravity and by molecular attraction, without forming an upper barrier of saturated soil which prevents the escape of the air below and the downward passage of the water. Where precipitation continues long and a considerable part of the water makes its way downward into the soil, through the belt of weathering to the belt of cementation, locally the belt of saturation or the level of ground water may rise almost or quite to the surface.

The water which passes to the belt of cementation is carried downward, as already explained, by gravity and molecular attraction. The proportion of the water of the belt of weathering which on the average passes into the belt of cementation is small. In the level arid regions the proportion which thus passes downward may be almost zero, and even in the humid regions only a small fraction of the water which gets into the belt of weathering passes through this belt into the belt of cementation.

UPWARD MOVEMENTS OF WATER.

The water which enters the belt of weathering and does not join the belt of cementation is brought to or above the surface (a) by molecular attraction or (b) by vegetation. In either case this water is evaporated. At times of abundant precipitation the evaporation is very small, but at intervals between precipitation, especially at times of sunshine and in warm climates, the water near the surface rapidly passes into the atmosphere. The water thus brought to the surface, as already intimated, is derived mainly from the belt of weathering, but a portion may come from the sea of ground water.

MOLECULAR ATTRACTION.

The manner in which the water is brought to the surface by molecular attraction, thus overcoming gravity, is fully discussed on pages 150–152. However, the proportion of the precipitation which is thus brought to

[a] Whitney, cit., pp. 160–161.

the surface is very difficult to estimate. It is everywhere an important force, but is more important in proportion as there is lack of vegetation. In the complete desert regions this force acts alone in returning the water to the surface. In such regions practically the entire precipitation may be returned to the surface by capillarity. This is likely to occur where, on account of sudden and abundant precipitation, a saturated layer forms above a layer not saturated, and especially where the layer below is dry. It has already been explained that under such conditions the water works its way downward with great difficulty, and, remaining near the surface, it is rapidly evaporated.

While much the larger part of the water returned to the surface by molecular attraction is the water of imbibition in the belt of weathering, a portion of the water may be derived from the belt of cementation, and thus pass upward entirely through the belt of weathering in reaching the surface. The effect of capillarity in raising the level of ground water above the normal level is spoken of on page 412 and on pages 150–152. It is also explained that, due to the attraction between the molecules of rock and water, water is drawn along the walls of the openings of the mineral particles beyond the height of the free surface.

The amount of water which may be transported upward a given distance by molecular attraction is a function of the absolute amount of pore space and the size of the openings. With a given pore space the amount increases with fineness of subdivision to a certain limit. The amount of surface of the particles increases as subdivision increases. Therefore, in finely subdivided material the wall space along which the water can creep is very much greater than in coarse material. To illustrate, it will be readily appreciated that the amount of water which capillarity would carry up from the free surface through a distance of 1 meter in a coarse grained sandstone is small as compared with that which would be transported upward for the same distance through a soil having the same absolute amount of pore space. But where the openings are so small as to be subcapillary the water adheres to the walls, and the amount of water transmitted decreases. Thus, through a fine clay having the same pore space as an ordinary soil, the amount of water transported upward would be less than in the soil.

The quantity of water which may thus move upward from the belt of saturation has been experimentally determined by King for some materials

under certain conditions. In an experiment carried on for forty days in coarse sands, in which the free surface of water was 15, 30, 45, 60, and 75 cm. below the surface, King found that the mean evaporation per day was 0.2895, 0.282, 0.203, 0.0864, and 0.0495 cm., respectively.[a] In the cases of the largest and the smallest numbers, those in which the level of ground water is 15 and 75 cm. below the surface, the amount of evaporation in a year would be 105.6675 and 18.0675 cm., respectively. "Where the movement is vertically upward through a distance of 1 foot [30 cm.] it has been found by experiment that the rate for a fine sand was 2.37 pounds per square foot [1.16 grams per sq. cm.] per day of twenty-four hours; when the lift was increased to 2 feet [60 cm.] the movement became 2.07 pounds [1.01 grams per sq. cm.]; at 3 feet [90 cm.] it was 1.23 pounds [60 grams per sq. cm.], and at 4 feet [120 cm.] only 0.91 pounds per square foot [0.444 gram per sq. cm.]. A similar trial with medium clay loam gave a movement of 2.05 pounds [1 gram per sq. cm.] for a lift of 1 foot [30 cm.], 1.62 pounds [79 grams per sq. cm.], for 2 feet [60 cm.], 1 pound [0.488 gram per sq. cm.] for 3 feet [90 cm.], and but 0.9 pound [0.439 gram per sq. cm.] where the lift was 4 feet [120 cm.]."

"The observations show that it [capillary movement] is very rapid at 4 feet [120 cm.]; so rapid, indeed, that were it maintained throughout the year it would deliver at the surface the equivalent of 63.85 inches [11.2 cu. cm. per sq. cm.] of water."[b] With finer but equally porous soils the amount of water thus derived from below the level of ground water may be considerably greater.

By "capillary movement," as used by King, is meant the process, already described, of creep along the walls to the surface above the free surface of ground water, not the raising of the surface in consequence of capillarity, as that term is ordinarily used. (See pp. 150–152.)

Cultivation greatly retards the process of the upward movement of water by molecular attraction. The upper part of the soil is in blocks separated by supercapillary openings. The continuous capillary openings in the soils and the close contacts are broken up. The amount of wall area upon which the water may creep upward is greatly reduced. The conditions prevent molecular attraction from readily bringing water to the surface, and evaporation is retarded. The intense heat from the sun during

[a] King, cit., p. 92.

[b] King, cit., p. 85.

the day mainly affects the cultivated layer. This contains but little moisture, and consequently evaporation is much slower than in areas where the capillary openings extend unbroken to the heated surface. Consequently soils cultivated as soon after precipitation as the water has had time to make its way to the subsoil may retain considerable amounts of water a short distance below the surface during long periods of drought.

VEGETATION.

In proportion as vegetation is present, this becomes an important influence working in conjunction with molecular attraction in the circulation of water in the belt of weathering. In another connection it will be shown that roots commonly permeate the soil both laterally and vertically. Ordinary herbaceous plants frequently have roots extending to a depth of 1 to 2 meters, and the roots of trees penetrate to a depth of 5 to 6 meters, or even 9 to 12 meters. The lateral extent of many plant roots is even greater than their vertical extent. In areas of abundant vegetation the upward movement of water is much more largely the result of plant roots than of molecular attraction. According to Merrill, in forested areas the total amount of evaporation and transpiration from the trees amounts to about 75 per cent of the total precipitation. In areas covered by other vegetation the total varies from 70 to 90 per cent, depending upon the character of the plants.[a] If these figures be correct, they show how important an agent the roots of plants are in the upward transfer of ground waters to the surface. In proportion as the region is arid the volume of the roots decreases. But even in the deserts the amount of plant life is surprisingly great. Moreover, in deserts the roots are often several times as extensive as the parts of the plants above ground, so that in such regions roots are very important factors in the circulation of the small amounts of water of the belt of weathering. It is only in the comparatively small areas where the deserts are absolute that roots are altogether wanting.

On the average, much the larger quantity of water brought to or above the surface by plants is derived from the belt of weathering. But it is clear that in many areas, and especially in low-lying areas, where the level

[a] Merrill, George P., Rocks, rock-weathering, and soils, Macmillan Co., New York, 1897, pp. 280–281.

of ground water is near the surface, the roots tap this water stratum and carry water from it to the surface.

In summary, while the lateral movements of water in the belt of weathering are of consequence, it is clear that the upward and downward movements are those of dominant importance. Gravity is always at work carrying the water downward; the roots are always at work carrying it upward. Molecular attraction following periods of precipitation works with gravity in carrying the water downward, and at intervals between precipitation works with the roots in carrying the water surfaceward, in opposition to gravity.

Thus, a large proportion of the water of precipitation takes a downward journey for a certain distance into the belt of weathering, and then returns to the surface. The chief impelling forces for the first part of the journey are gravity and molecular attraction, and the impelling forces in the return journey are roots and molecular attraction working against gravity. Where vegetation is sparse or wanting, the upward movement by which water is brought to the surface is chiefly or wholly molecular attraction.

VARIATION IN LEVEL OF GROUND WATER.

Variation in the level of ground water is of great importance in rock alteration, since due to this a certain horizon is alternately under conditions of the belt of weathering and under those of the belt of cementation. It follows that the contrasting reactions of these two belts are superimposed upon each other. Variation of the level of ground water has an exceptional importance in connection with ore deposits. (See Chapter XII.)

Variation in the level of ground water depends upon many factors, of which (1) variable precipitation, seepage, and evaporation, (2) uplift and subsidence, (3) denudation and valley filling, and (4) man, produce important results, and (5) barometric pressure and (6) temperature produce unimportant effects.

PRECIPITATION, SEEPAGE, AND EVAPORATION.

The surface of the ground water rises and falls (a) with climatic change resulting in variations in precipitation, (b) with variations in precipitation running through several years, (c) with seasonal variations in precipitation, and finally (d) with the cyclonic and diurnal variations in precipitation.

(a) As a result of climatic changes there may be very great variations in precipitation in different epochs in the same region. For instance, there is every reason to believe that in the Great Basin during Glacial time precipitation was abundant, whereas at the present time precipitation is sparse. At the epoch of abundant precipitation there were in this region vast fresh-water lakes, such as Bonneville and Lahontan. At this time of humidity it is highly probable that the level of ground water was comparatively near the surface, while at the present time for much of the region it is a considerable distance below the surface. Similar climatic changes affected much of the western part of the United States and have affected other parts of the world at various periods of geologic time.

(b) Besides these great climatic changes there are in many parts of the the world alternating cycles of several years or a decade, during a part of which there is more than an average precipitation, followed by other years in which the precipitation is less than normal. At times of abundant precipitation the level of ground water rises; at times of deficient precipitation it falls. The rise and fall in the level of ground water due to such cycles may amount to several meters. It not infrequently happens that wells sunk during the humid part of a cycle have to be sunk deeper during the part of the cycle in which the precipitation is small. During the closing half dozen years of the nineteenth century California experienced the dry part of one of these cycles. As a consequence of the deficient precipitation vegetation very greatly suffered. During these years in southern California the level of ground water markedly fell at various places from 5 to 10 or even 20 meters. For instance, in the Los Angeles Basin, in the area above where the river emerges from underground, during the years 1895–1899 the level of ground water fell at the rate of between 0.3 and 0.4 meters per kilometer per annum in passing upward from the source of the river. But in southern California the fall in the level of ground water is very largely due to the influence of man. (See pp. 427–428.) Pumping of ground water to the surface for irrigation, and not variation in precipitation, is one of the main causes of this fall.

(c) The greater part of the earth has either one or two seasons of relatively abundant precipitation, followed by one or two less wet or dry seasons; therefore the cycle of seasonal variation is semiannual or annual.

The variation in the level of ground water due to this cause may be exceptionally 2 or 3 meters, but in general is but a fraction of a meter.

(d) The cyclonic intervals of varying precipitation in the north temperate zone are usually from three to seven days. However, in various regions, at various times, several of the cyclonic periods may rapidly follow one another, and give conditions of almost continuous rainfall. In certain regions, as in the Tropics, a chief variation in precipitation is diurnal, there being in the region of the doldrums abundant showers almost daily. Ordinarily the variation in the level of ground water due to the cyclonic period is but a few centimeters; but locally, and where there is nearly continuous precipitation for a day or more, the level of ground water may rise, due to this variation in rainfall, by amounts as great as a meter, or, very locally, several meters.

The rise of ground water for a given amount of precipitation in any cycle depends not only upon the quantity of the rainfall, but upon the amount of seepage into the soil, and this depends upon many factors. For instance, low declivity, vegetation, rough surface, and large openings are favorable to entrance into the soil; while steep declivity, lack of vegetation, and small openings are favorable to large run-off and evaporation. Where there is a high percentage of seepage a comparatively small precipitation may raise the surface of ground water a considerable amount, for the pore space at the level of ground water may be small. In case the pore space were 10 per cent, a fall of 1 cm. would produce a rise in ground water of 5 cm., provided one-half of it reached the level of ground water through seepage. In many districts increased seepage, due to irrigation, has markedly raised the level of ground water.

In so far as the water evaporated is derived from the belt of cementation, this tends to lower the level of ground water. The amount of this lowering, due to the upward transportation of water through molecular attraction and vegetation, is likely to be great in proportion as the level of ground water is near the surface. Where the level of ground water is many meters below the surface the variation due to this cause is probably small. The variations of the level of ground water due to evaporation are considered in connection with precipitation and seepage; for in many regions the abundant precipitation occurs at the same periods of the year

at which the evaporation is the most rapid. These two factors frequently tend to neutralize each other so far as the level of ground water is concerned, for the effect of precipitation is to raise the level of ground water and the effect of evaporation is to lower that level.

The variations in the level of ground water due to climatic variations in precipitation are the greatest, but the variations of the level of ground water due to seasonal variations in precipitation, or even to cyclonic and diurnal variations in precipitation, are far more important than might at first be thought, for these lesser variations largely or wholly compensate for their smaller magnitude by their much greater frequency.

UPLIFT AND SUBSIDENCE.

Vertical movements of the earth's crust take place as a result of either epeirogenic or orogenic movements, or the two combined. Uplift tends to lower the ground water, and subsidence tends to raise it, in reference to a fixed plane in the rocks. Only regions which have a considerable elevation above the sea have the ground water far below the surface. Regions which are near the level of the sea usually have the ground water near the surface; but this may not apply to interior low-lying deserts.

DENUDATION AND VALLEY FILLING.

Consequent upon denudation there is a steady downward movement of the level of ground water. This continues, unless compensated for by uplift, until base-level is reached, when the ground-water level approximately corresponds, on the average, with the ocean. The result of denudation is continuously to transfer the upper part of the belt of cementation into the belt of weathering, and thus to change the conditions of alteration from those of one belt to those of the other. This steady downward migration, in reference to a fixed plane in the rocks, of the boundary between the belt of weathering and the belt of cementation is the most important of all the changes in the variation of the level of ground water, leading to profound geologic and economic consequences, which are fully discussed elsewhere. Variation in the level of ground water may also result from valley filling. When a valley is filled to a considerable depth, this may result in corresponding rise in the level of ground water. If the valley be again excavated, this may lower the ground water to its former level.

INFLUENCE OF MAN.

Man influences the level of ground water in various ways. Probably his most important effect upon this level is by the denudation of the forests, by irrigation, and by cultivation. It is well known that commonly the removal of the forests increases the run-off. It has been explained (p. 415) that bad cultivation may increase the run-off and that good cultivation diminishes it. But, also, cultivation increases greatly the amount of evaporation. All changes in the quantity of run-off, in the redistribution of the run-off by irrigation, and in the amount of evaporation from the surface, produce an effect upon the level of ground water. In general the effect of cultivation is to lower the level of ground water. This is illustrated in hundreds of localities within the area of the lake plains. In many places where before cultivation began there were shallow lakes, marshes, or swamps in which the ground-water level was at the surface, the ground water is now 5 to 10 meters below the surface. For instance, in central Wisconsin, southwestern Portage County, in the vicinity of Almond and Bancroft, in the gravelly and sandy outwash plains bordering the Wisconsin drift, Dr. Weidman states that in consequence of cultivation the ground-water level has been lowered from 6 to 12 meters, and the level of water in the ponds and lakes lowered from 3 to 4 meters, so that the area of lake and pond waters is not more than 25 to 50 per cent of what it was fifty years ago, when settlement of this vicinity first began. In Clark County, in the area of thick old drift overlying sandstone and crystalline rock, since settlement began forty years ago the level of ground water has been lowered from 3 to 4 meters.

Man has further modified the level of ground water by drawing upon the sea of ground water. He has sunk innumerable wells from which large quantities of water have been taken. This drawing of the water to the surface lowers the level of ground water. However, the effect was probably comparatively slight until the developments of the last century. During that period great numbers of artesian wells were bored, from which very large quantities of water are taken. The inevitable result of the opening of the numerous ready passages for the ground water to again reach the surface must be the lowering, at least to a small extent, of the level of ground water at the feeding areas. But probably the most important lowering of the level of ground water is in mining and irrigation

districts, where within comparatively small areas vast quantities of water are raised to the surface. The ground-water level in many mining areas has been locally lowered scores or even hundreds of meters. From the Comstock lode enormous quantities of water were pumped.[a] From a single iron mine in the Lake Superior region 19,000 liters per minute have been raised for considerable periods of time. In the lead and zinc district of Missouri many small pumps located close together have lowered the level of ground water at various places from 30 to 50 meters. Drafts upon underground water by pumping for irrigation and for city supplies have lowered the level of ground water to a very considerable extent in many of the semiarid regions. An excellent illustration is furnished by southern California, where during the last ten years the level of ground water has been lowered at various places over extensive areas from 10 to 30 meters.

Depression of the level of ground water due to pumping rapidly transfers a considerable horizon from the conditions of the belt of cementation to those of the belt of weathering, and thus accomplishes the same effects which are slowly produced by the downward migration of the level of ground water due to other causes.

BAROMETRIC PRESSURE.

King has shown that barometric pressure may slightly raise and lower the level of ground water. The fluctuations due to this cause are, however, usually but a fraction of a centimeter.[b]

TEMPERATURE.

It has already been seen that increase in temperature decreases the viscosity of ground water. At times of increase of temperature, therefore, the escape of the underground waters through springs and seepage is promoted, and the level of ground water is lowered. At times of decrease of temperature the escape is stayed. Also rise of temperature produces increased pressure, due to the expansion of the gases confined in the soil above the ground water, and King holds this to be the chief cause of increase of flowage with increase of temperature.[c] However, the effect of the temperature factor upon the level of ground water is slight, its most important effect being slight daily oscillations.

---

[a] Lord, Eliot, Comstock mining and miners: Mon. U. S. Geol. Survey, vol. 4, 1883, pp. 231–232.
[b] King, F. H., cit., p. 76.
[c] King, F. H., cit., p. 75.

GENERAL STATEMENTS.

The variations in the level of ground water where they are considerable are very slow, but in amount they are of great consequence. Of the factors which separately, or more commonly by combination, have produced marked variations in the level of ground water, uplift, subsidence, denudation, valley filling, and the influence of man are the most important. The lead and zinc districts of the Mississippi Valley afford excellent illustrations of variations in the level of ground water. In the lead and zinc districts of the upper Mississippi Valley, near the close of the Glacial epoch, there was a subsidence and valley filling to the amount of 60 to 90 meters or more. This produced a corresponding rise in the level of ground water, and the transfer of a considerable belt which had been in the belt of weathering to the belt of cementation. Possibly the same thing has happened in the lower Mississippi Valley lead and zinc region. For instance, in the Joplin district of Missouri, below the level of ground water, there were large caves before mining began. These caves may have been formed when the level of ground water was at a lower horizon, so that the surrounding ground was in the belt of weathering. At a time when a horizon now in the belt of cementation was in the belt of weathering solution was the dominant process. When the level of ground water rose, this horizon passed into the belt of cementation and deposition and consequent filling of the openings began. As a result in the Joplin district the caves are gigantic geodes lined with great crystals of calcite, some of them from 10 to 50 or more centimeters long. By the artificial lowering of the level of ground water by mining processes this belt has been again transferred to the belt of weathering, and reactions characteristic of this belt have been set up.

METAMORPHISM IN THE BELT OF WEATHERING.

VARIABLE MATERIALS AND CONDITIONS OF BELT OF WEATHERING.

Within the belt of weathering there is the greatest variety of materials and conditions. The reactions are therefore of the most extraordinarily complex character. In the belt of rock weathering there is the greatest possible variety of rocks. In fact, every known variety of rock which exists anywhere upon the earth may be present. There are in this belt

original igneous rocks of every variety, from plutonic to volcanic, including both lavas and tuffs; rocks varying from the most dense to the most porous, such as pumice; rocks varying from the most basic to the most acid, and having the most variable mineralogical composition. A second class of rocks which has even a more widespread occurrence in the belt of weathering than the igneous rocks are the sedimentary rocks. These include mechanical sediments of all kinds, chemical and organic sediments of all kinds, and all possible gradations between them. A third class which is present in the belt of weathering is the metamorphosed rocks of igneous and sedimentary origin. These rocks may have been altered either in the zone of anamorphism or in the belt of cementation. Moreover, the amount of alteration is variable, ranging from rocks which have been but slightly affected to those which have been mashed and granulated or recrystallized throughout. Fourth, there is every variety of surficial rocks produced by the transporting agents of wind, water, and ice. Moreover, all these four classes of rocks are present in the belt of weathering in various stages of alteration under the conditions of that belt, so that the products vary from those in which the forces of weathering have produced but slight effects to those in which they have produced final results.

Within the belt of weathering all the agents of metamorphism are present. These include gaseous solutions, water solutions, and organic compounds. Oxygen, carbon dioxide, water, nitrogen, and other gases are present in variable proportions. Of these the first three are of greatest consequence. In humid regions, at times of abundant precipitation, the belt of weathering becomes nearly saturated with water, and these gases may be nearly or quite excluded except as they are contained in the water solutions. In desert regions there may be an almost complete lack of water, even that held by imbibition being evaporated by the heat of the sun near the surface. At such places the gases dominate. In the lower part of the belt, in consequence of the variation of the level of ground water, is a layer which has alternately conditions of saturation and conditions in which water, carbon dioxide, and oxygen are together in important amounts and in various proportions. Therefore the conditions are those ranging from saturation by water solutions to saturation by gaseous solutions.

It follows from the above that the amount of gaseous solutions is inversely as the amount of water solutions. When the water solutions

occupy much of the space, this leaves little space for the gases. On the other hand, in so far as water does not occupy the openings in the rocks, this space is taken up by the gases which may exist anywhere in the belt of weathering. Varying amounts of water solutions and gaseous solutions furnish favorable conditions for the gases to pass into the water solutions, in which form they are most effective in rock alteration.

Further, in the belt of weathering there is a great variety of plant and animal life, and consequently the complex action of organic bodies upon the inorganic compounds. These organic forms vary in magnitude from the smallest bacteria to large trees. Moreover, the organic bodies act both while alive and after death. Therefore reactions of many kinds result from them, involving gases, liquids, and solids.

Furthermore, in the belt of weathering there are great variations in temperature and other physical conditions. The temperature varies from far below 0° C. in polar regions to 50° C. or even 60° or 70° C. in the sun in some of the arid regions of the Tropics. For much of the globe, as a result of varying temperature, the surface water is alternately in the form of liquid and of ice. Also the conditions are those of variable pressure.

Finally, there are all variations in topographic conditions. Some areas show very slight relief, while others have the most abrupt slopes. Some areas are near sea level, others are 3,000 or more meters above sea level.

The work in the belt of weathering is accomplished by mechanical and chemical agencies. The mechanical work is largely that of disintegration; the chemical work is largely that of decomposition and solution. Disintegration may entirely separate the constituent minerals from one another, or even subdivide the mineral particles. Decomposition is complete when all of the original minerals have changed to other minerals. Solution is complete only when all the original minerals are dissolved. The ultimate result of the action of the mechanical and chemical agencies is to produce soils.

MECHANICAL WORK.

Mechanical work subdivides the rocks or disintegrates them. Mechanical work is accomplished by the following: (1) Water, (2) ice, (3) wind, (4) change in temperature, (5) change from water to ice, (6) plants, and (7) animals.

WATER, ICE, AND WIND.

In the broadest sense wind, water, and ice above the surface are included under the agents of the belt of weathering. But this subject is so large that it is ordinarily given a separate treatment under the terms erosion, land sculpture, or physiography. Therefore the work of these three agents will not be here considered or even summarized. However, it may be well to recall that these agents are not efficient in the mechanical disintegration of the rocks except as they use rock material as their tools; that is, wind, water, and ice are incapable of rapidly cutting the rocks. When the wind bears sand it may do a considerable amount of cutting; when water bears rock material varying in size from bowlders to silt it may accomplish a vast amount of work. The same statement is true of ice. All three of these agents, therefore, furnish their energy of motion to rock material as tools of cutting, and thus accomplish mechanical destruction of the rocks. This energy is indirectly derived from the sun and gravity. It should also be said that there appears to be a limit beyond which water, wind, and ice are incapable of finer subdivision of material. Thus Daubrée found that in water there was a limit beyond which mechanical trituration for the hard minerals like quartz ceased, "owing to the buoyant action of the water, which in the form of a thin film between adjacent particles acted as a cushion and prevented actual contact to the extent necessary for mutual abrasion."[a] Shaler appeals to the same principle in explaining the endurance of sand grains on the seashore. He says that the grains are held apart by films of interstitial water (this would be water of adhesion), and are therefore prevented from strongly impinging against one another.[b] Judd says that the small particles of the alluvial deposits of the Nile which have been transported great distances are angular, while the larger particles of the same deposits are subangular or rounded. Judd attributes the rounding of the larger grains to eolian rather than river work;[c] but this does not lessen the force of the argument as to there being a lower limit beyond which the particles are not rounded by river action.

---

[a] Merrill, cit., p. 197. See Daubrée, A., Géologie expérimentale, Paris, 1879, p. 268 et seq.

[b] Shaler, N. S., Phenomena of beach and dune sands: Bull. Geol. Soc. America, vol. 5, 1894, pp. 208–209.

[c] Judd, J. W., Report on a series of specimens of the deposits of the Nile Delta, obtained by the recent boring operations: Proc. Royal Soc. London, vol. 39, 1885, pp. 213–220.

Abrasion by wind, and especially by ice, may give a finer subdivision of material than abrasion by water. For instance, it is well known that glacial débris varies in coarseness from great bowlders to a silt so fine that the streams issuing from the glaciers are of whitish color, and it takes many days for the exceedingly finely divided material to settle when a stream has passed into a lake. Chamberlin and Salisbury found, as a matter of observation, that the particles of loess of the Mississippi Valley smaller than 0.1 mm. in diameter are angular.[a] This accords with the conclusion of Daubrée that particles smaller than 0.1 mm. in diameter are not reduced in size by their mutual trituration, since the particles of the loess have been carried for long distances in water. However, the particles as originally formed by glacial abrasion may be very much smaller than this. Indeed, Chamberlin and Salisbury state that only 1.3 per cent of the particles of loess of the Mississippi Valley are as large as 0.005 mm. in diameter, and that probably 90 per cent of the particles do not reach half this size.[b] The loess of the Rhine gave similar results, there being here only seven-tenths of 1 per cent of material over 0.01 mm. in diameter, only 3 per cent between 0.005 and 0.01 mm., while 85 per cent is less than 0.0025 mm.[c] The lower limit of size of the particles of the loess are not given by any of these writers, but nothing is said which intimates that it goes below the limit of visibility of the microscope.

It thus appears tolerably certain that, however fine the subdivision by any of the mechanical agents, the finest subdivision of material is only accomplished by chemical agents.

For instance, in the residuary soils of the driftless area of Wisconsin—material largely subdivided by chemical agents—less than six-tenths of 1 per cent of the particles are as large as 0.005 mm. in diameter, less than 1.5 per cent are between 0.005 and 0.00285 mm., and about 98.5 per cent are smaller than 0.00285 mm.[d] In this case much of the material is so finely divided that it is stated that "since the visible proportion of exceedingly fine particles was greatly increased with each increase of magnifying power,

[a] Chamberlin, T. C., and Salisbury, R. D., The driftless area of the upper Mississippi Valley: Sixth Ann. Rept. U. S. Geol. Survey, 1885, p. 246.

[b] Chamberlin and Salisbury, cit., pp. 279–280.

[c] Chamberlin and Salisbury, cit., p. 280.

[d] Chamberlin and Salisbury, cit., pp. 248–249.

the number at the limit of vision was always great."[a] It thus appears that in the case of chemical subdivision it is doubtful if the microscope used fully resolved the material into its constituent particles.

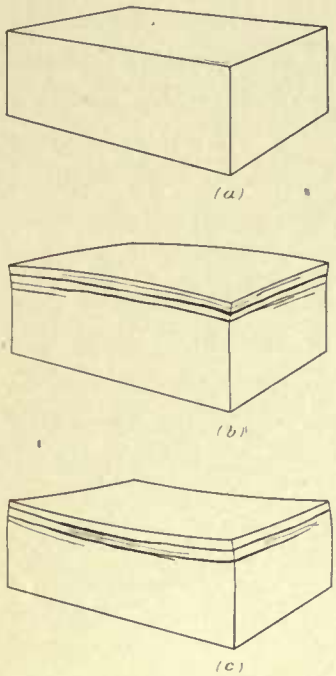


FIG. 6.—Effect of unequal heating of the surface of a rock. (*a*) shows the condition of a block of uniform temperature. (*b*) illustrates the manner in which the upper portion of a rock surface expands when heated above average temperature; where the difference in temperature is sufficiently great, this results in the splitting off of the upper layers. (*c*) illustrates the contraction of the upper surface by cooling below the average temperature; where the difference in temperature is sufficiently great, this results in the splitting off of the upper layers.

CHANGE IN TEMPERATURE.

Change in temperature results in the disintegration of the rocks by producing differential expansion and contraction. When the rock surface is affected by any change in temperature, the heat is only slowly conducted and there is differential expansion between the outer part of the rock and the inner part. In other words, powerful shearing stresses are set up, as a result of which flakes of the rock are disrupted from the deeper located solid material (see fig. 6).

The surface temperature may be greater or less than the average temperature of the rock, and the process is especially effective when the surface temperature is alternately lower and higher than the average temperature.

The expansion of different rocks per degree centigrade varies from less than 0.000023 cm. to about 0.000046 cm. per meter. When these numbers are multiplied by the number of degrees of change during any period—as, for instance, one day—we have the increment of change in the lengths of the rocks at the surface during the period. Suppose the change for a given day to be 40° C., and the length of the rock surface be taken as 1 meter at the mean temperature, then its length at the coolest period will be from 0.99908 to 0.99954 cm., and at the hottest period from 1.00046 to 1.00092 cm. A few inches below the surface it may be assumed that the temperature of the rock is near the mean; consequently, at the coolest part of the day the surface of the rock is shorter than the rock below, and at the hottest part of the day it is

[a] Chamberlin and Salisbury, cit., p. 248.

longer than the rock below. When the surface is shorter than the main mass of the rock below, if the elastic limit be surpassed tensile fracture will take place nearly at right angles to the surface. When during the hot part of the day the surface is longer than the average of the rock below, powerful shearing stresses are set up parallel to the surface. If these surpass the elastic limit of the rock, shearing rupture will take place roughly parallel to the surface. When once a rupture is started, it will extend until the rupture feathers out at the surface or until the flake or spall has become long enough to permit the stresses to be relieved by buckling.

The surface scaling of rocks, and parting parallel to the surface exfoliation, are attributed to differential expansion and contraction caused by change of temperature, because the fractures are peripheral. In massive rocks, whatever the topographic forms and shapes, the scaling produced by temperature changes should be roughly parallel to the surface. For instance, if there be a great dome of granite, the fractures which form should circumscribe it (see Pl. I) as they would circumscribe a sphere, being at any given place parallel to it. In the United States such fracturing is well exhibited by the granite of Dunn Mountain, in North Carolina; by the granite domes of central Missouri; and above all by the great granite domes of the West, such as those in the Sierra Nevada. The scales are ordinarily but a few centimeters in thickness, and are rarely more than 60 cm. thick. Of course, in none of these cases does every fracture occur precisely parallel to the surface; rather, they are inclined to it at small angles in various ways, thus frequently intersecting. However, the correspondence is, in a general way, as given, and therefore the positions of the fractures furnish evidence of their production in consequence of shearing stresses due to changing temperature.

Another reason for believing that the peripheral or zonal scaling and parting are due to changing temperature is the fact that the ruptures occur nearly parallel to the surface without reference to previous structures. Thus it often happens that great slabs, 2 cm. to 5 cm. thick, of schistose or gneissic rocks form, which are diagonal or even at right angles to the structures.

The changes in temperature are important in proportion as the rate of change and the amount of change are great. It is rapid change of temperature which mainly results in differential expansion and contraction, and therefore this is the factor of final consequence. The temperature changes are (a) diurnal, (b) cyclonic, and (c) seasonal. The amount of the diurnal change is considerably less than that of the cyclonic, and that of the cyclonic change is considerably less than that of the seasonal; but the rate of change is far greater for the diurnal than for the cyclonic, and this is far greater than the seasonal rate. Therefore the diurnal changes are the most important in the disintegration of rocks, the cyclonic changes of next importance, and the seasonal changes are of least importance.

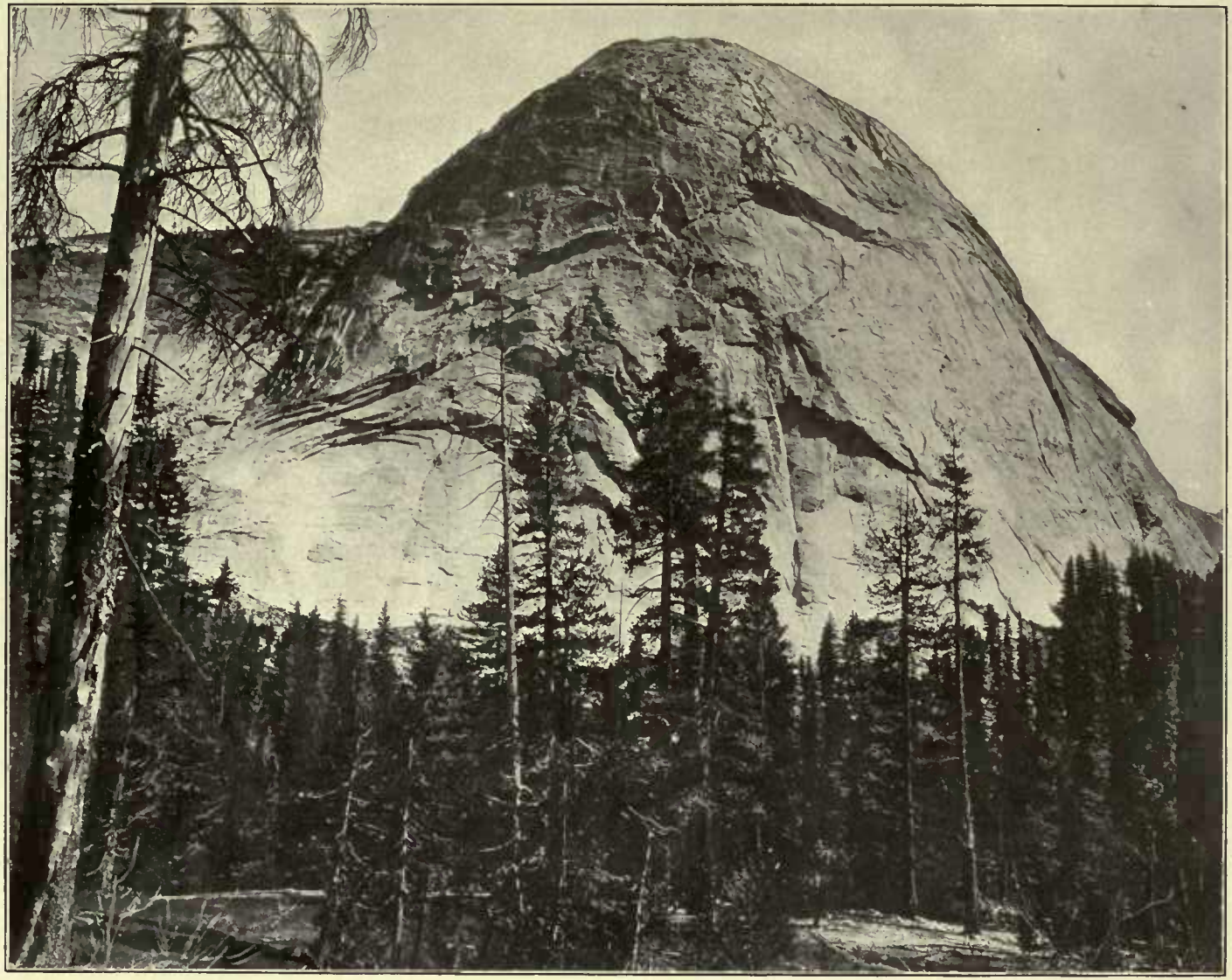
The diurnal changes range from 0° to 50° C. or more. For instance, in Texas the diurnal changes in temperature in the shade are frequently 30° to 40° C.[a] Branner states that in Brazil the diurnal change of temperature from the minimum at night to the maximum in the sun frequently amounts to 50° C., the average appearing to be not far from 40° C.[b] In some desert regions diurnal changes even greater than this have been recorded. Probably even these ranges are not great enough; for the sun beating upon the surface of a rock will raise it to a higher temperature than it will a thermometer in the air. In order to obtain the real effect of the diurnal change of temperature, one ought to sink a thermometer in the exposed rock surface and ascertain its range from the coolest part of the night to the hottest part of the day.

While the diurnal range is very great, probably the diurnal change of temperature and the resultant fracturing is limited to a few inches in depth.

The changes in temperature due to the cyclonic period are greater than those due to the diurnal period, but the period is longer and the rate of change is much less. The cyclonic period produces a variation of temperature which runs over several days; its effect may therefore be felt more deeply than the diurnal range, and it is not improbable that the fractures from a few centimeters to several meters below the surface and parallel to the surface in many massive rocks are largely the result of the cyclonic change of temperature. Such fractures are well exhibited in many granite quarries. The scaling probably mainly due to the diurnal and cyclonic

[a] Fourth Ann. Rept. Geol. Survey of Texas, 1892, p. 144.

[b] Branner, J. C., Decomposition of rocks in Brazil: Bull. Geol. Soc. America, vol. 7, 1896, p. 286.



FAIRVIEW DOME, SIERRA NEVADA, FROM THE NORTH.

Illustrates the manner in which granite spalls parallel to the periphery as a result of expansion and contraction due to changes in temperature.

changes in temperature has usually been called exfoliation. Walther, referring to the agency of the sun in producing change of temperature of rocks, has named the process insolation, and of it he gives many instances.[a]

The annual ranges of temperature in various parts of the United States run from 30° C., as at San Francisco, to 67° C., as at Moorehead, Minn. Gannett says that in the interior of Alaska the annual range is sometimes as great as 80° C.[b] Hahn agrees that the annual range of temperature in some regions is as high as 70° to 80° C.[c] While the seasonal changes of temperature are therefore greater than the diurnal or cyclonic changes, the times of the changes are far greater, and therefore the rates of the changes far less. While the seasonal change undoubtedly produces some effect in disintegrating the rocks near the surface, probably the more important effect of the seasonal change is at a greater depth than the diurnal or cyclonic changes. At a depth of 1 or 2 meters, or at most several meters, the diurnal or cyclonic effect must be obliterated. Since the seasonal effect some meters below the surface is produced very slowly, probably this effect is not determined by the maximum range of temperature, but by the range of the hottest season of summer compared with the coldest season of winter, for a long period of time is required in order to produce an effect of differential expansion more than a meter or two below the surface. If January be compared with July, the change in temperature in the arctic regions would be from about 45° to 60° C., the change in the temperate regions would be from about 20° to 45° C., and the change in the tropical regions would be from about 10° to 20° C. If the comparison were made of January and February together with July and August together, these numbers would be but little different. Since the annual changes of temperature are small in the tropical regions, are much greater in the temperate regions, and are very great in the arctic regions, it follows that, so far as the annual changes in temperature are concerned, the effect is a minimum in the tropics and a maximum in the arctic regions. The seasonal changes of temperature produce an effect to a depth of 12 to 15 meters. Probably the effect which can be discriminated from the diurnal and cyclonic changes is between 3 or 4 to 12 or 15 meters. It seems to me probable that many of the joints

[a] Walther, Johannes, Die Denudation in der Wüste und ihre geologische Bedeutung: Abhandl. Math.-phys. Classe Gesell. Wiss. Leipzig, vol. 16, 1891, pp. 448–453.

[b] Gannett, Henry, The general geography of Alaska: Nat. Geog. Mag., vol. 12, 1901, p. 191.

[c] Hahn, Julius, Handbuch der Klimatology, J. Engelhorn, Stuttgart, 1883, p. 497.

of massive rocks parallel to the surface which may be noted between these limits are the result of seasonal changes in temperature.[a]

The disintegrating effect of changes of temperature is most marked in those regions in which the precipitation is small for at least a portion of each year. The reason for the great activity of the process during dry periods is plain. On account of the low humidity the sun is very effective. For the same reason the radiation is rapid at night. Consequently there are very rapid changes of temperature, and hence very great exfoliation. These conditions of lack of humidity are ideally illustrated in the desert regions. In such areas it is well known that insolation is very rapid.[b] However, probably insolation is not so rapid in those deserts in which there is no precipitation as in those in which there is occasionally abundant precipitation. The conditions for insolation are furnished by the dry periods extending from one to several years. When the very abundant precipitation, perhaps in the form of cloud-burst, comes it transports the loosened material away from the parent rock and leaves it bare for further insolation. This condition of affairs is well illustrated in the desert regions of the United States. Also insolation may be very rapid in regions which are considered humid, provided a period of each year is dry. This is well illustrated by Brazil, where there are alternately wet and dry seasons. During a dry season insolation loosens the material; during the wet season the water transports the loosened material to the lower ground, and thus exposes the fresh rocks to insolation during the next dry season.

In regions in which the precipitation is plentifully distributed over all parts of the year, insolation is small, for the rocks become covered by vegetation, which prevents the direct action of the sun. In the humid temperate parts of the world are many regions in which insolation is at a minimum, such as the southern Appalachians and the Olympic Mountains.

---

[a] Since the above was put in type Gilbert has said: "In many dome-like granite hills the rock is divided into plates by curved joints approximately parallel to the surface. Some observers call the structure exfoliation; others regard it as an original structure of the granite. Under one view the surface forms determine the structure; under the other the structure determines the surface forms. A study of the High Sierra of California in the summer of 1903 has led me to accept the former view, and to believe that the forms of the parting planes are conditioned by the forms of the topography. As to the cause of the phenomenon the following hypothesis is advanced: Formed deep within the crust, the granite was initially subject to compressive stress, which was balanced by internal expansive stress. As the unloading involved in subsequent denudation reduced the compressive stress, the unbalanced expansive stress caused strains which eventually resulted in exfoliation." Gilbert's view has much in its favor for many of the deeper joints parallel to the surface, but it does not exclude the formation of ruptures as above described. Indeed the two causes may work together.

[b] Merrill, Rocks, rock-weathering, and soils, p. 283. Walther, cit., pp. 448–453.

Topography is also an important element in insolation. Where the slopes are steep gravity pulls off the flakes formed, and new surfaces are exposed to the process. Also theoretically the greater the elevation the more the insolating effect, for the sun does not have to pass through so much of the atmosphere and should be more effective in heating, and the heat gained in the day should be more rapidly radiated at night. Thus one would expect greater changes in the temperature of the rocks at high elevations than at low elevations, but I am not aware that observations have been made on this point.

Rocks vary greatly in their power to resist the effect of insolation. Sandstones are refractory; limestones and shales are somewhat less so; crystalline rocks, especially those having a large amount of readily cleavable feldspar, are most affected. I suspect the cause of the varying resistance of rocks is a function of their porosity. In proportion as the rocks have many pores, such as sandstones, the expansion and contraction is taken up between the grains, and therefore rupture is not likely to take place. Where, however, the rock is a solid continuous mass, with little or no pore space, when the temperature of the surface is higher than that of the rock below, the expansion can be taken up only by elasticity. When the stresses accumulate beyond the elastic limit, ruptures are produced. (See p. 434.)

Frequently insolation results in burying the crystalline rocks, except the sharpest peaks, beneath débris. Regions which well illustrate the disintegration largely due to change of temperature are southern California and the peninsula of Lower California, described by Merrill[a] and by McGee;[b] Egypt, described by Walther;[c] and Brazil, described by Branner.[d]

Where the rocks become covered with flakes and spalls, this of course protects the solid rock below, and thus stays the process of insolation.

Disintegration as a result of insolation can be certainly discriminated in the low-lying regions of the Tropics, in which the temperature never falls below 0° C. But in all areas in which the temperature frequently falls below 0° C. the disintegrating effect of insolation is conjoint with that of freezing and thawing, next considered.

---

[a] Merrill, George P., Sketch of Lower California: Bull. Geol. Soc. America, vol. 5, 1894, p. 499.

[b] McGee, W J, The formation of arkose: Science, new ser., vol. 4, 1896, pp. 962–963.

[c] Walther, cit., pp. 347–569.

[d] Branner, J. C., Decomposition of rocks of Brazil: Bull. Geol. Soc. America, vol. 7, 1896, pp. 281–294.

CHANGE FROM WATER TO ICE.

When water changes to ice it expands 9 per cent. According to Dewar, the decrease in the freezing temperature of water corresponding to an increase of pressure of one atmosphere up to 700 atmospheres is 0.0072° C. per atmosphere. It follows from this that in order to prevent the change from water to ice taking place at temperatures below 0° C. very great pressures must be exerted. These pressures are shown by the following table:

Pressures required to keep water liquid at temperatures below 0° C[a].

	Atmospheres.
C.	
−1°	138.888
−2	277.777
−3	416.666
−4	555.55
−5	694.44
−18 to −20	13,000

It follows that where water is in rocks and the temperature is below 0° C., in general the rocks are not strong enough to resist the change of the water to ice; therefore an expansion of 9 per cent takes place. When this expansion occurs one of two things happens. The water obtains the additional space by pushing aside the material of the soil or rock or by expanding into openings not fully occupied by the water. The latter is especially likely to occur in rocks in which the water is that of imbibition and which therefore are not saturated.

In such cases the space between the particles of the rocks, as, for instance, grains of soil or grains of sand in a sandstone, is so great that the expansion of freezing need not move the grains with reference to one another. In general it may be said that, in proportion as the rocks approach saturation, disruption is likely to occur; in proportion as the amount of contained water becomes small, disruption is not likely to take place.

[a] See Mousson, A., Einige Thatsachen betreffend das Schmelzen und Gefrieren des Wassers: Ann. der Physik und Chemie, J. C. Poggendorff, vol. 105, Leipzig, 1858, p. 161.

As shown by Buckley,[a] the efficiency of the change of water to ice in disintegrating the rocks is largely dependent upon the readiness with which the water from a saturated rock can escape. If the pore spaces are large and continuous, as in sandstones, even where the rocks have been recently saturated, as by a heavy rain, a large part of the water readily and quickly escapes, so the water held long enough to freeze is mainly that which adheres to the grains or is the water of imbibition. If the pore spaces are not nearly full when the small amount of water is frozen there is room for expansion without disrupting the grains, and consequently there is very little effect in the way of disintegration. Hence a very porous rock where drainage is easy may be comparatively little affected by repeated freezing and thawing. On the other hand, if a rock be fine grained, so that the pore space, while of the same volume as in a sandstone, is very much subdivided, the water of imbibition and that of saturation approximate to each other; the water escapes much more slowly; the pore spaces may be nearly full for some time, and freezing is therefore much more likely to disintegrate the rock. Such rocks are illustrated by the chalks.

Further, in rocks which have a very small amount of pore space, and in which the pore spaces are more or less discontinuous or are subcapillary, so that the water is held firmly, the destructive effect of the freezing of the small amount of water may be very great, because the pore space is full and expansion must cause disruption.

The relation of size and continuity of pore space to disintegration by freezing is well illustrated by the resistance of sandstones as compared with granites and limestones. The Dunnville sandstone of Wisconsin has the remarkably large pore space of 28 per cent. Buckley repeatedly saturated specimens of this stone with water and immediately exposed them to temperatures below 0° C., but the water so rapidly escaped that the strength of this rock was "proportionally less affected by freezing and thawing than the strong granites and limestones, having low percentages of pore space."[b] In contrast with this is the behavior of Cleopatra's Needle, a granite monolith in Central Park, New York, which, after having resisted for thousands

[a] Buckley, E. R., Building and ornamental stones: Bull. Wisconsin Geol. and Nat. Hist. Survey No. 4, 1898, p. 382.

[b] Buckley, cit., p. 382.

of years the weathering forces in Egypt, where diurnal temperature changes are great, began so rapidly to disintegrate under conditions of freezing and thawing that it had to be coated with paraffin to exclude water and save it from complete destruction;[a] but in this case it should be remembered that the effect of change from water to ice is superimposed upon the effect of past centuries of insolation. Perhaps its rapid disintegration was due to minute openings between the grains, formed by insolation, which the water could enter. It is rather probable that stone fresh from the Egyptian quarry would not disintegrate so rapidly.

When water is in large, deep clefts, such as joints, and freezing takes place, the result is to widen the cracks. Furthermore, it is to be noted that at times of alternate freezing and thawing the process is cumulative. After the openings have been somewhat enlarged and the ice melts, the rock does not fully return to its original position, and when freezing again occurs the widening again takes place, and so on. Thus the process may begin with the subcapillary openings and by repeated freezing and thawing widen them to large openings. At each time of expansion the ice acts as a wedge, and besides widening the cracks it may also extend them, and thus the process of freezing and thawing enlarges cracks already formed and also extends them.

In addition to the size and extent of the openings and the amount of contained water, further factors affecting disintegration by freezing and thawing are topography and latitude. In proportion as the slopes are sharp and the elevation is great the effect is likely to be great. The disrupting effect is especially strong on cliffs and mountain sides and is slight where the topographic variation is slight. It has already been seen that the depth to which the effect may be produced varies from nothing to a number of meters, and thus it is confined, under the most favorable circumstances, to the mere outer skin of the earth. The great effectiveness of the change from water to ice in disintegrating rocks on steep slopes is due to the fact that the material disrupted is quickly pulled away from the parent rock by gravity or is transported elsewhere by moving water or ice and a new surface is exposed to the action of freezing water.

Illustrations of rapid disintegration due largely to freezing and thawing are afforded by many of the higher mountain slopes, if not by nearly

[a] For discussion of relations of size of pores to destructive effect by freezing and thawing, see Buckley, cit., pp. 20–25, 382–384.

every mountainous region of the world the peaks of which extend above the snow line. For instance, the top of Grays Peak, in the Front Range of Colorado, is a mass of disrupted fragments, the solid rock being nowhere exposed. Mount Dana, in the Sierra Nevada, furnishes an illustration of the disintegration of a schistose rock. Here also the top of the mountain is a mass of disrupted blocks, the solid rock protruding only here and there.

As to latitude, it is certain that in the lowlands of the Tropics, where the temperature does not fall to 0° C., the effect of freezing and thawing is nil. But in the north temperate and frigid regions where there is a long season of alternate freezing and thawing, the effect is very great. The rapidity of the disintegration of rocks in areas like Greenland and Spitzbergen is largely explained by the alternate freezing and thawing. Cushing has described the argillites of the region of Glacial Bay as disintegrating with amazing rapidity.[a]

It is impracticable wholly to discriminate the above-described disintegrating work of freezing and thawing from that of insolation. Insolation is everywhere at work, although, as has been explained, with variable power. It is common to attribute the work of disintegration in temperate and arctic regions wholly to freezing and thawing, but it is plain that the disintegration in such regions is partly the result of insolation.

A further effect of freezing and thawing, fully described by Merrill, is the movement of materials already disintegrated. The movements may affect pebbles and bowlders as well as fine material. As the soil below a pebble or bowlder freezes it expands upward, this being the direction of least resistance. When the soil thaws, the fine material falls back more readily than the bowlders, and thus leaves the pebbles and the bowlders slightly higher than before.[b]

Oftentimes in saturated tough clay soils, after the surface layer of water and soil has frozen, and thus forms a congealed sheet, as the process of downward freezing continues the necessary space required by the expansion in the change from water to ice is obtained by the water breaking through the crust at very numerous points. As the water is slowly squirted up through these pipes it congeals at the points of issue, just as it does when

[a] Cushing, H. P., Notes on the Muir Glacier region, Alaska, and its geology: Am. Geol., vol. 8, 1891, p. 224.

[b] Merrill, George P., Rocks, rock-weathering, and soils, Macmillan Co., New York, 1897, pp. 393–394.

water is frozen while confined in a deep, strong vessel. This squirting upward at the various openings produces innumerable ice pipes. Where a surface sheet of ice had formed before the restraining frozen sheet of soil and water together were produced the ice pipes may raise it above the surface. In a similar manner frequently a sheet of the congealed surface soil and vegetation separates from the frozen material below less knit together with roots. This is frequently very destructive to vegetation. As the solidified surface of soil containing the roots of the various plants is pushed upward the roots are broken and a crop of grain may thus be completely destroyed. The ice, soil, and vegetation may be raised 5 or 10 cm. from the surface. Thus we have a sheet of frozen material above the ground, supported by innumerable minute pillars of ice. When first seen the phenomena appear almost magical. All of the above phenomena are strikingly illustrated in southern United States.

PLANTS.

The mechanical effects of plants in disintegrating rocks is mainly accomplished by means of the roots, which first penetrate the soil and later, at any given place, expand in size. They thus exert very considerable pressure against the surrounding material, and universally, in the case of soil, and frequently, in the case of rocks, push the material aside. In some instances where the roots find lodgment in a crevice of a strong rock they are unable to exert sufficient pressure to widen the openings, and as the roots grow they become flat. Tree roots under such conditions may have become so flat that their breadth is many times their thickness. However, in such cases, it is very certain that the roots exerted great pressure against their confining walls. The plants which first take possession of the rock surface are usually of the smaller kinds. Later larger plants appear, and finally, plants of the largest size may obtain a foothold. The depth to which the action of the roots extends is a function of the size of the plant. The plants may, perhaps, be divided for the present purposes into (a) lichens, mosses, and other small plants; (b) cacti; (c) grass, grain, and vegetables; and (d) shrubs and trees.

Lichens, mosses, etc.—Lichens, mosses, and other small plants may take possession of the bare rock, sending their tiny rootlets into the minute joints or other fractures, or even into the pores between the grains. They thus

exert a powerful effect in the disintegration of the rocks and help to form a thin soil, which is gradually taken advantage of by the larger plants.

Cacti.—Cacti and similar plants may be very effective in breaking up the rocks and producing a soil, because able to exist with a small amount of moisture. Storer states that the lava beds of Etna are planted with a prickly pear. The roots of the cacti soon crack the lava and in a few years it breaks up to a sufficient depth to allow vineyards to be planted. By the same sort of action cacti are breaking up the amygdaloidal rocks of the pyramids of old Mexico.[a] The cacti are very abundant in the semi-arid and arid regions, and consequently in such countries produce their most important effect.

Grasses, grains, and vegetables.—Grasses and grains may exist on a very thin soil, but under favorable conditions the roots penetrate to considerable depth. Many of the grasses send their roots into the soil several meters. The roots of the red clover are known to extend a meter into the ground; those of barley, wheat, and oats may penetrate 2 or more meters. In the case of corn, careful experiments have shown that for the depth of 2 meters or more the soil may be permeated with roots, so as to constitute a remarkable tangle, fully occupying all the distance between the hills. But as to size and extent of roots probably the most remarkable of the plants cultivated is alfalfa. It is well known that the roots of this plant often extend to a depth of 6 meters, and the soil is commonly a tangle of alfalfa roots and rootlets to the depth of 3 to 5 meters. Cases are recorded where the roots have been found in sandy soils at river banks at a depth of 15 to 18 meters below the surface.[b]

Shrubs and trees.—Shrubs and trees may extend their roots several or many meters from their base, both laterally and vertically. Of the shrubs, mesquite is one of the more remarkable. This plant in the arid regions sends a tangle of roots several meters below the surface; indeed, the amount of vegetable fiber below the surface is so much greater than that above the surface that the roots are frequently dug out for fuel, as furnishing a better supply than the growth above the surface. Second-growth black oak has been known to extend its roots laterally more than 9 meters beyond its

[a] Storer, F. H., Agriculture in some of its relations with chemistry, Charles Scribner's Sons, New York, vol. 1, 1887, pp. 130–131.

[b] Smith, J. G., Leguminous forage crops: Yearbook of the Dept. of Agric., 1897, p. 494.

base and 1 meter below the surface. Apple trees have been known to send roots 14 meters from their bases. In one case a long-leaf pine in Alabama was found to have extended its roots to a depth of 9 meters, and at this depth the taproot had a diameter of 20 cm. It is to be presumed that the gigantic trees of western America and the Tropics extend their roots even deeper.

In this connection it is to be remembered that various kinds of plants work together. For instance, in warm humid regions trees are very numerous. Between the trees are other plants of many kinds. Thus we are lead to the conclusion that wherever the vegetation is luxuriant above the surface of the earth there is almost an equally luxuriant growth below the surface. Wherever there is a cornfield, a wheat field, or a clover field, corresponding with the plexus of stems and leaves above the ground there is another plexus of roots below the ground almost equaling that above the ground in extent, and pervading it throughout with roots varying in size from the most minute hair-like rootlets to the taproots of the plants. Wherever there is a forest the great bulk of trunks and limbs and twigs above ground is almost paralleled below ground by the tangle of roots, grading from the mighty taproot to the minute rootlets.

As the roots grow they thrust the soil or the rock aside. As they decay, openings are left which are taken advantage of by downward-moving water. Gravity tends to pull the soil or rock together again, and thus finally close the larger openings. But in the meantime others are made by the growing vegetation. Thus where there is abundant plant life the rock material to the depth to which the roots extend is being constantly moved about.

Therefore, if we would understand the entire work of the plants, wherever we see the foliage of field or forest above the ground we must in our mind's eye see a nearly equal volume of roots below the surface of the earth, prying the soil apart, splitting the rocks, and, as explained below, acting upon them chemically.

Finally, when large plants, especially trees, fall a further mechanical effect follows. It has already been seen that trees may extend large roots into the ground to a depth of a number of meters, both laterally and vertically. When a tree is overthrown by the wind, or in some other way, a large mass of the soil, subsoil, contained bowlders, and even the solid

rock, may be lifted 1, 3, or 5 meters above the surface level. When the trees decay the inorganic material again joins the soil, producing a mound. The material of the mound is in a much disintegrated and decomposed state; for it has been in a position to be effectively acted upon by all forces of weathering. How important this effect is can be appreciated only when one travels through the original forests. In such places there are seen almost everywhere hollows where trees have been uprooted and mounds where the material has fallen to the surface. Where tornadoes have swept through the forests, all the trees in their paths have been overthrown at once, and it seems as if almost the entire mass of soil and rock to a depth of several meters had been upturned. This process is well illustrated in the Lake Superior region. The paths of the tornadoes vary from 30 meters to 2 kilometers or more in width. In traveling through the forests of this region one may find the paths of recent tornadoes, those a few years old, and those many years old. Where tornadoes have recently cut through the forests the giant trees have been uprooted and thrown down in a tangled mass like jackstraws. Where the tornadoes occurred a few years ago the fallen trees are dead and a tangle of briers, brush, and saplings is between the tree trunks, presenting a smooth surface above, but the whole making an interwoven mass of live and dead vegetation, which presents all but an impassable obstacle to travel. Still later the fallen trunks show marked decay, and at this time the saplings have become small trees. After many years the great tree trunks and roots are ridges of rotten wood, so decayed that one's foot may pass through them, and the inorganic material held by the roots has fallen to the earth again. The saplings have become trees, but they may be discriminated from the older trees of the adjacent forest. In the final stage of decay one may recognize the path of a tornado by numberless earth mounds, where the soil and rocks have been lifted up by the roots and fallen back, but the second-growth trees can scarcely be discriminated from those of the adjacent forest.

ANIMALS.

Burrowing animals are very numerous, and they, like the plants, have an important mechanical effect upon the rocks in the belt of weathering. The effect of animals is, however, somewhat different from that of plants, in that the animals frequently move the soil in a definite direction rather than in

various indefinite directions, as do the plants. The main mechanical effect of the burrowing animals is to bring material from below the surface to the surface. But some animals throw the soil behind them or push it up as they move along. The animals which are mechanically effective upon soil are (a) earthworms, (b) ants, termites, and other insects, (c) larger burrowing animals, and (d) man.

Earthworms.—As shown by Darwin, one of the most important of all the animals in movements of the soil, if not the most important, is the earthworm.[a] Earthworms are distributed throughout the world in great numbers. According to Darwin there are at work in many places over 50,000 upon a single acre of soil. The amount of material which the earthworms transport to the surface of the earth in a year is very great. Darwin estimates it as over 18 tons [16 tonneaus] per acre.[b] Davison states that the amount of earth turned up by lobworms is sometimes 3,147 tons [2,832 tonneaus] peracre.[c]

Ants, termites, and other insects.—According to Branner, of the burrowing work of insects that of ants and termites is most important. In tropical regions these "are vastly more important as geologic agents than the earthworms of temperate regions."[d] However, this statement should doubtless be restricted to the mechanical work of turning over the soil and bringing it to the surface. In chemical work the earthworms are probably more important. (See p. 456.) The ant-hills of the Tropics are of great size and incredibly numerous. Branner states that the ants of Brazil live in large, often enormous, colonies. They excavate in the earth chambers with galleries which radiate and anastomose in every direction, and into these chambers and galleries they carry great quantities of leaves. One can get some idea of the extent of these openings from the heaps of earth brought up by the insects. These mounds are often from 15 to 30 meters long, from 3 to 6 meters across, and from one-third to over 1 meter high, and contain tons of earth.[e]

In another place Branner states in reference to the ant-hills in the forests: "These mounds are from 3 to 14 feet [1 to 4½ meters] high and

[a] Darwin, Charles, The formation of vegetable mould, D. Appleton & Co., New York, 1883, pp. 1–313.

[b] Darwin, cit., p. 165.

[c] Davison, Charles, Work done by lobworms: Geol. Mag., new ser., vol. 8, 1891, p. 491.

[d] Branner, J. C., Ants as geological agents in the Tropics: Jour. Geol., vol. 8, 1900, p. 152.

[e] Branner, J. C., Decomposition of rocks in Brazil: Bull. Geol. Soc. America, vol. 7, 1896, pp. 255–314.

from 10 to 30 feet [3 to 9 meters] across at the base. The new ones are steeply conical and the old ones are rounded or flattened down by the weather. In many places these mounds are so close together that their bases touch each other. About the Urucú station the ant-hills are so thick that the country looks like a field of gigantic potato hills."[a]

The termite nests, above the average surface, are said by Branner to be from one-third to 3½ meters in height, and from one-third to 3 meters in diameter. He further says that along the upper Paraguay he has seen "places where the nests are so close together that one could almost walk upon them for several hundred yards [one-half a kilometer] at a time, while over many acres of ground no one of the nests was more than 10 feet [3 meters] from another."[b] Branner further states that innumerable anastomosing galleries are made underground from a depth up to 3 meters or more. "The underground galleries of the saúbas penetrate the soil to great distances. These ants are very injurious to vegetation, and one of the methods used by the planters to kill them is to blow poisonous fumes into their burrows. I have seen these fumes, blown into one of these openings, issue several hundred, even 1,000, feet [312 meters] away."[c]

Even in the temperate regions in favorable locations the number of ant-hills on an acre is very great, and each hill may vary from one to several feet in diameter, and from a few centimeters to a meter in height. Shaler calculates that the ants in a certain field in Massachusetts transfer annually half a centimeter of material from the subsoil to the surface. He explains the freedom from pebbles of certain sandy soils of New England resting upon a subsoil containing pebbles as due to the upward transportation of the soil by the ants in making their mounds.[d]

Besides ants and termites there are many other small burrowing animals, such as beetles and wasps, but these are comparatively unimportant.

The larger burrowing animals.—The larger burrowing animals are very numerous. Of these some of the more important are the prairie dog, rabbit, mole, badger, woodchuck, gopher, and ground squirrel. In many regions

[a] Branner, J. C., Ants as geologic agents in the Tropics, cit., p. 151.

[b] Branner, J. C., Decomposition of rocks in Brazil, cit., p. 299.

[c] Branner, J. C., Decomposition of rocks in Brazil, cit., p. 296.

[d] Shaler, N. S., The origin and nature of soils: Twelfth Ann. Rept. U. S. Geol. Survey, pt. 1, 1891, p. 280. Merrill, George P., Rocks, rock-weathering, and soils, Macmillan Co., New York, 1897, pp. 389–390.

of the West, especially in the great plateaus, colonies of prairie dogs occupy areas extending each from less than an acre to many acres. Throughout one of their towns are burrows and corresponding hillocks in every direction, at intervals from less than a meter to a few meters. Different varieties of gophers and ground squirrels are very widespread. They occur from the Atlantic to the Pacific. In some areas in the West their burrows and mounds are only less numerous than those of the prairie dogs in the dog towns. The mole is scarcely less effective than the prairie dog and ground squirrel. In many areas the ridges produced by his work as he makes his way underground are everywhere intersecting. He works alike in field and in forest; in the South and in the North; in the lowland and high up in the mountains under the snow. In the forests of the mountains, just after the snow has melted, the intersecting ridges are often so thick that a person can scarcely step without crushing one of them. The rabbits in Australia have multiplied in an amazing way. Their burrows are innumerable. In Cape Colony there is said to be almost constant movement of the ground due to the various animals. In various parts of the West, especially in the semiarid regions, the ground has been so penetrated with burrowing animals that in riding rapidly great care must be taken lest one's horse break through the crust into the holes. Blake says that in Tulare Valley, California, "mules often break through the thin crust and sink to their shoulders in these holes."[a]

Man.—Finally, man is the most important of all the mechanical organic agents. He has stripped the soil of its protective vegetation, including both grasses and forests, for large parts of the world. As a consequence of this the transporting power of running water has been multiplied for these areas many fold. Wherever there are fields the rivulets run turbid to the brooks. Not only is the denuded soil transported seaward with many fold the speed of natural conditions, but in many fields where cultivation is carelessly carried on or is neglected there form gulleys and deep ravines which cut through the subsoil or to the very bottom of the belt of disintegration, or even into the solid rock. A plexus of ravines once formed rapidly deepens and extends, and thus carries on the process of transportation with ever-accelerating speed.

---

[a] Merrill, cit., p. 394.

Marsh,[a] Shaler,[b] Merrill,[c] and others have strongly emphasized the ravages upon the soil as the result of man's work. They show how even from man's point of view the present careless methods of cultivation will in the future work to his disaster. However, for the present purpose I wish to emphasize the fact that as the soil is transported to the streams and to the ocean new material is exposed to the forces of disintegration and decomposition, and thus the process of weathering is accelerated far beyond the speed under natural conditions.

General statements.—In conclusion, we see that the animals, from the earthworm, ant, and termite to the larger burrowing animals, throughout all parts of the earth which are thickly inhabited by animals, are constantly working over the soil to a considerable depth. By the work of these animals there is a constant migration or movement of material from the soil or subsoil to the surface, where the material is directly exposed to all the weathering agencies. Man has denuded a large part of the surface of the earth of its protecting vegetation. Thus, as a consequence of the work of all the animals, the soil is more ready to be caught up by running water and transported to the streams. This has other far-reaching consequences in furnishing increased amounts of sediments and salts to the sea, and consequently greatly accelerating the speed of upbuilding of the sedimentary rocks. Hence animals perform a very important mechanical function in weathering the rocks, in promoting their transportation, and in exposing new surfaces to the weathering forces; and consequently they greatly accelerate denudation and deposition.

CHEMICAL WORK.

Chemical work is accomplished by all the agents of metamorphism, viz, (1) plants, (2) animals, (3) water solutions, and (4) gaseous solutions. These agents will first be considered and then their joint work.

---

[a] Marsh, George P., Man and nature, or physical geography as modified by human action, Chas. Scribner & Co, New York, 1869, pp. 576–577.

[b] Shaler, N. S., The origin and nature of soils: Twelfth Ann. Rept. U. S. Geol. Survey, pt. 1, 1891, pp. 329–339.

[c] Merrill, George P., Rocks, rock-weathering, and soils, Macmillan Co., New York, 1897, pp. 396–398.

THE AGENTS.

PLANTS.

Chemical work is done by plants both while alive and when dead.

PLANTS, ALIVE.

The most important chemical action by the nonbacterial plants is that of the abstraction of carbon dioxide from the atmosphere and its reduction and combination with other elements so as to produce the various vegetable tissues. The amount of carbon dioxide in the air is exceedingly small, not more than from about 2.76 to 3 volumes in 10,000. Therefore the air in the belt of weathering where plants do not exist can not be presumed to contain more than this proportion of carbon dioxide, except for the very small amount which is brought down by the rain, estimated by Branner in Brazil to be 0.0065 in 1,000 parts by weight.[a] However, by the action of the chlorophyll-bearing plants, which include all of the large and many of the small plants, and by the action of the "red, brown, and blue-green algæ," and by one class of bacteria,[b] carbon dioxide of the atmosphere is reduced and the carbon is concentrated in the plants mainly as cellulose ($nC_6H_{10}O_5$) or woody fiber. This contains 44.4 per cent of carbon. The cellulose produces no marked geological effect so long as the plants are alive; but when dead and acted upon by bacteria, oxygen, and moisture the cellulose furnishes a number of active acids which produce very important geological results. (See pp. 461–465.)

Plants contain combined nitrogen, but the great majority of plants are unable to obtain their nitrogen from the air; they must use that which is already in a combined state in the soil. A large part of this combined nitrogen is that furnished by the decay of earlier plants and animals. (See pp. 465–466.) But some combined nitrogen is brought to the soil from the air. For instance, in manufacturing, combined nitrogen often escapes in the form of ammonia, and ammonia may also evaporate from the ocean. But this combined nitrogen was derived from earlier plants or animals, and therefore we have as yet no original source for combined nitrogen.

But it is well known that the nitrogen of the air is to some extent combined with other elements by electric discharge, and thus we have an

[a] Branner, J. C., Decomposition of rocks in Brazil, cit., p. 305.

[b] Fisher, Alfred, The structure and functions of bacteria, translated by A. Coppen Jones, Clarendon Press, Oxford, 1900, p. 107.

original source of combined nitrogen. The combined nitrogen of the air may possibly be absorbed directly from the air by plants, but it is mainly useful when brought down by rain, snow, dew, fog, etc. However, the amount of nitrogen precipitated from the air, including both that which is secondary to plants and animals and that which is originally produced, is very small, only 1 or 2 kilograms per annum per acre.[a]

We have therefore yet to account for the main original source of combined nitrogen. Recent discoveries have shown that there are certain bacteria that are capable of utilizing the nitrogen of the air. The Leguminosæ, such as peas, beans, etc., form numerous nodules upon their roots, which become the hosts of these bacteria,[b] and finally abstract the nitrogen fixed by the bacteria. Thus the bacteria abstract and the leguminous plants store nitrogen compounds in the fruits, stalks, and roots. Experiments show that where leguminous plants are grown and turned under, the gain in nitrogen for the soil is rapid and the accumulation of combined nitrogen great; and this gain is certainly largely due to the capacity of the bacteria and leguminous plants together to use the free nitrogen of the atmosphere.

Certain bacteria are able to fix free nitrogen without the assistance of other living plants.[c] Whether the plants obtain their nitrogen from the nitrates already in the soil, or, like the leguminous plants, help to produce the combined nitrogen, the material is mainly built into albuminous compounds or proteids.

From the foregoing it follows that there are two original sources of combined nitrogen in the soil—that combined with other elements through the agency of plants, and that combined with other elements through the agency of electricity. Material from each of these sources is built into the body of the plants, as already seen, mainly in the form of proteids. The material so long as it is in this form has no important geological effect, but when plants decay these compounds become the source of the nitrogen acids and salts which are important geological agents. (See pp. 465–466.)

Besides concentrating combined carbon and nitrogen in the belt of weathering, live plants have a direct chemical effect upon the rocks. It is

[a] Aikman, C. I., Manures and manuring, Wm. Blackwood & Sons, London, 1894, p. 119.

[b] Fischer, Alfred, The structure and functions of bacteria, trans. by A. C. Jones, Clarendon Press, Oxford, 1900, pp. 88–97.

[c] Aikman, cit., pp. 96–97.

well known that plants abstract certain ingredients from the soil, and therefore exert a soluble effect. The inorganic materials which are most abundantly abstracted are potash, soda, magnesia, lime, phosphoric acid, and silica. The relative proportions of these substances in grain and straw, as given by Johnson, are as follows:[a]

	Grain.	Straw.
Potash	18.5	12.0
Soda	3.9	4.6
Magnesia	7.0	3.0
Lime	2.7	7.3
Phosphoric acid	32.4	6.0
Silica	31.1	59.7

Besides these substances, the plants also abstract such compounds as iron, sulphur, and chlorine in small amounts. The sulphur is absorbed as a sulphate.

Finally, living plants have a further effect upon the rocks. Fresh roots give acid reactions, and as a consequence, where they are in contact with the rocks they corrode them chemically. This is illustrated by the action of lichens and creepers and by the corroded surfaces of rocks where roots are in contact with them. In some cases where the rocks are rather readily soluble, as, for instance, limestone, actual furrows may be produced in the rocks as a result of the solution.[b] In places where lichens occur the rocks may be softened to a depth of 2 to 4 centimeters.[c] Johnson states that "on the Schwalbenstein, near Glatz, in Silesia, at a height of 4,500 feet [1,368 meters], the granite is disintegrated under a covering of lichens, the feldspar being converted into kaolin or washed away, only the grains of quartz and mica remaining unaltered."[d]

Positive evidence that the chemical action of the plants is important is furnished by experiments showing that soils upon which plants have been grown are more soluble after all the parts of the plants have been removed than are similar soils in which no plants have been grown.[e]

---

[a] Johnson, S. W., How crops feed, Orange Judd & Co., New York, 1870, p. 364.

[b] Storer, F. H., Agriculture in some of its relations with chemistry, Charles Scribner's Sons, New York, vol. 1, 1887, pp. 187–188.

[c] Storer, cit., pp. 130, 131.

[d] Johnson, cit., p. 142.

[e] Storer, cit., p. 186.

PLANTS, DEAD, AND BACTERIA.

Thus far the work of plants during their upbuilding has been considered. However, there is a class of plants the chief geological work of most of which is the destruction of other plants and animals. Of these the bacteria are by far the most important. The number of bacteria in the soil is almost incredibly great. "Ordinary earth may yield anything from 10,000 to 5,000,000 per gram, whilst from polluted soil even 100,000,000 per gram have been estimated."[a] Certain authors include some of the fungi, and especially the molds and yeasts, under plants which assist in the destruction of other plants and animals. This assistance seems to be in the way of absorbing compounds of other plants and animals, and building them into new forms which may be more readily attacked by the bacteria. Certain it is that the process of oxidation, both of the chlorophyll-bearing plants and of the fungi, is a bio-chemical one, the main organic agents in which are the bacteria. In this matter the bacteria are one of the most potent factors of all the organic geological agents. Since this process of oxidation of plants and animals is mainly accomplished after death by the living bacteria, the geological work of the bacteria is mainly considered in connection with dead plants and dead animals.

When plants die they fall to the earth, and the part above the surface may become buried to a greater or less extent in the soil. The roots of the plants below the surface, nearly as great in mass as the parts above the soil, are buried to a depth, as already seen, from a few centimeters to 10 meters or more. After this material dies it decomposes or is oxidized.

The oxidation of the carbon, nitrogen, and hydrogen of plants is the conjoint result of bacteria, water, and oxygen. The process of the decomposition of the plants might go on in the presence of moisture and oxygen even if bacteria were not present. However, experiments show that the process of oxidation would be very slow indeed if it were not for the oxidizing bacteria. We have already seen that the bacteria are present in the soil in enormous numbers. The oxidizing bacteria act in different ways. They oxidize the carbon, and with water convert it into carbonic acid; and they oxidize the combined nitrogen of plants into ammonia, nitrous acid, and finally into nitric acid.

---

[a] Newman, George, Bacteria, Putnam's Sons, New York, 1899, p. 137.

Bacteria, water, and oxygen decompose the iron and other sulphides. They further oxidize the iron of carbonates. While oxidation is the rule for the belt of weathering, under exceptional conditions bacteria, moisture, and vegetation, or the two latter, may deoxidize instead of oxidize compounds, and this may result in the reduction of ferric salts and in denitrification. These processes of oxidation and deoxidation are fully considered on pages 461–473.[a]

ANIMALS.

The chemical work of animals is accomplished while alive and while dead the same as that of the plants.

ANIMALS, ALIVE.

In chemical work probably the most important of the animals while alive are the earthworms. It has already been seen how great is the number of these animals, and how great is the mechanical work which they accomplish. These animals differ from other animals in that they pass the soil directly through their alimentary canals, so that the active compounds of the body act upon and decompose the inorganic materials. It is impossible to estimate the effect of this repeated passage of the soil through the alimentary canals of the earthworms, but it can not be doubted that it results in dissolving a vast quantity of earth materials and in rendering undissolved parts of the materials more soluble.

The ants and termites carry a large amount of vegetable material from above the surface of the ground to below the surface, and thus introduce it into the soil, so that when it decomposes the products formed will be most effective in their chemical action. Branner states: "The quantities of vegetable matter carried into their burrows is almost beyond belief. I have seen a full-grown orange tree completely stripped of its foliage within a few hours. In the coffee regions the damage done by them is so serious that the Brazilian Government at one time offered a large premium for a successful *formicida* or ant exterminator."[b]

A second effect of living animals comes from their constant excreta. These consist in large part of active chemical compounds, of which perhaps

[a] See Branner, J. C., Bacteria and the decomposition of rocks: Am. Jour. Sci., 4th ser., vol. 3, 1897, pp. 438–442.

[b] Branner, J. C., Decomposition of rocks in Brazil: Bull. Geol. Soc. America, vol. 7, 1896, p. 297.

the most important is uric acid. All over the world, above ground and below ground, excreta of all kinds are being added to the soil, or introduced by the burrowing animals below its surface, and the chemical effect upon the inorganic material of the soil can not but be very great.

Man has promoted chemical work in various ways. It has been pointed out that cultivation exposes the soil to the transportational agencies, and this continually exposes new material to chemical agents. Crops are planted and grown. When the crop matures it is removed, and the soil is again free from its active living plants. Thus there is continual alternation between abundant and sparse plant life, and consequently conditions very favorable for chemical reactions. Further, it is explained on pages 463–465 that man has oxidized great quantities of the organic material entombed in the earth during past geological ages, and thus increased the amount of the active chemical agent, carbon dioxide, in the atmosphere; and this of course has accelerated to an unknown extent plant growth and chemical action.

ANIMALS, DEAD, AND BACTERIA.

Animals die both below and above ground. When dead their bodies decompose and ultimately produce water, carbon dioxide, nitrates, some free hydrogen and free nitrogen, and some sulphates. This process of change to the ultimate products is accomplished by the bacteria, fungi, oxygen, and water, precisely the same as in the plants. The process is one of oxidation and is considered under that heading. (See pp. 461–466.) As with the plants, the process concentrates carbon dioxide, nitrates, and other compounds in the belt of weathering, thus placing important chemical agents in a very favorable position to do active geological work.

WORK OF SOLUTIONS.

It has already been explained that in the belt of weathering there are gaseous solutions, water solutions, and various mixtures of these which are at work upon the rocks. The very important gases are oxygen and carbon dioxide. It has been pointed out (pp. 76–81) that the activity of water solutions is dependent upon (a) the compounds present, (b) the temperature, and (c) the pressure.

(a) The water solutions are likely to contain considerable amounts of the salts formed by the union of the bases and acids which ordinarily occur

in rocks. In the ground water they are ordinarily composed of compounds consisting of the bases sodium, potassium, calcium, magnesium, iron, and aluminum, and the acids, carbonic, hydrochloric, nitric, hydrosulphuric, sulphuric, and phosphoric, and also colloidal silicic acid. Nitrous, sulphurous, and organic acids are also present. These bases and acids unite in various ways to produce many salts, the majority of which are, however, simple salts, such as the carbonates of the alkalies and alkaline earths.

Of these salts the dominant ones are those of sodium, potassium, calcium, and magnesium in the form of carbonates, sulphates, and chlorides. Furthermore, there are present other bases and acids which are omitted because of their subordinate quantity. For instance, in some cases various salts of manganese, copper, silver, gold, etc., are present, but the quantities of such compounds are so minute as to have no significance except in connection with ore deposits.

The water, moreover, contains oxygen, carbon dioxide, and other gases in solution. Where the rocks are not saturated by water gaseous solutions also are present and active. Of these oxygen and carbonic acid are the most important active chemical agents.

While it is well established, as explained (p. 63), that pure water acts upon all of the compounds which occur in nature, the activity of solutions is very greatly increased by the mineral content. This is true of bases, of acids, and of salts alike. Where bases or acids are present it is well known that the activity of solutions is greatly increased; but it has not been always fully appreciated that the same is true in reference to normal salts.

Therefore all of the above compounds, in all their forms, are actively at work in decomposing the rocks. The amount of work which any one compound does depends upon the strength of its bases or acids, and also upon its quantity, or upon the law of mass action. While if the compounds are present in equal quantity the stronger bases or acids do more work, it is frequently the case that a weaker compound more than compensates for this weakness by its great abundance. Illustrating this is carbonic acid, which, while very weak, is on account of its abundance, one of the most potent agents in the alterations of rocks in the belt of weathering.

(b) The temperature is of very great importance in the activity of the water and gaseous solutions.

The average annual temperature near the Arctic Circle in northern North America and northern Asia is about —15° C.; and from this temperature the average temperature varies to about —18° C. in northern Greenland. In the Temperate Zone the average temperature varies from about —15° C. in its northern part to about 22° C at its southern part. The Tropical Zone varies in temperature from about 20° C. to about 27° C. In central North America and central Asia the normal average temperature is about 5° C., in southern North America and southern Asia it is from 15° to 20° C. For the present purpose the average temperatures, rather than the changes of temperature or the extremes of temperature, are the data of first consequence; for the average action of solutions upon the rocks, extending through years, is controlled by these average temperatures. In the arctic and north temperate regions, during the time the temperature is below 0° C., it is highly probable that the decomposition of the rocks practically ceases; as the temperature rises above 0° C. decomposition begins, and this goes on with increasing speed in proportion as the temperature is high. Therefore, in the above facts as to temperatures we have in large part the explanation of the slowness of the decomposition of rocks in the arctic regions and the rapidity of the decomposition in the tropical regions.

It is to be noted that the activity of the solutions in the warm climates, as compared with the cold climates is much greater than would be inferred from the absolute temperatures. The temperature of northern Greenland (—18° C.) is 255° absolute; that of the Tropics (27° C.) is 300° absolute. Thus the ratios of the absolute temperatures between the extreme cold of the arctic regions and the warmth of the Tropics is as 255 to 300, a difference of less than one-fifth; but it is certain that the activity of the solutions in the Tropics is manyfold greater than in the arctic regions.

While the average temperature is the matter of most significance in this connection, the changes of temperature have an important effect upon the chemical decomposition of the rocks as well as upon the mechanical disintegration. From the tables given above it appears that while the average temperatures in the arctic regions are very low for certain seasons of the year the temperature for a whole month may average as high as 10° C., and during the day the temperature may rise as high as 20° C. At such temperatures it is certain that the process of decomposition of the rocks

takes place. Thus it appears that at certain seasons the temperature is high enough for decomposition to affect the rocks in the most northern and the most southern latitudes. But in polar regions the temperature is such that decomposition takes place for only a small fraction of each year; in the temperate regions the temperature is high enough for decomposition to take place during more than half the year; while in the Tropics decomposition is continuous. It therefore appears that in passing from the polar to the tropical zones we pass from a minimum to a maximum of chemical decomposition.

(c) As to the pressure in the belt of weathering, since the ground is not ordinarily saturated by water there is commonly no hydrostatic pressure; and the pressure at which the chemical reactions take place is therefore that of the atmosphere. At sea level the average pressure is that of a column of mercury 760 mm. high, or 1.0333 kg. per sq. cm. From the pressure at sea level the pressure diminishes as the altitude increases, and at the tops of the higher mountains is not more than about one-half of the amount at sea level. Not only is there change of pressure due to elevation, but there is change of pressure due to variable meteoric conditions. As a storm sweeps over an area the pressure is ordinarly low; at the clear intervals between the storms the pressure is usually high. Commonly the change in barometer from a low to a high is not more than 2 cm. and the average change is probably not more than 1 cm. Infrequently the change is 5 cm., or about one-fifteenth of the total pressure. Very exceptionally the change of pressure may be much greater than this. Probably these changes in pressure are so slight as to produce little effect upon the water solutions. But, as already shown (p. 61), the quantity of atmospheric gas acting is directly as the pressure. To illustrate, if the barometric pressure rises from 715 mm. to 760 mm., the proportional increase in the amount of gas action is about one-fifteenth. More frequently, however, the variations are from one-thirtieth to one-fiftieth, or even less.

Since the amount of gas is directly as the pressure, it is evident that, so far as this factor goes, the higher the barometer the greater the activity of the gases at work in the belt of weathering. But since the variations in pressure due to this cause are ordinarily but a small fraction of the total pressure, the variations in effect are not sufficiently great to be appreciable. Since, in reference to the cyclonic periods, the times of high pressures are

usually those of low temperatures, and vice versa, so far as increased pressure produces an effect it compensates to a slight extent for the low temperature, and decreased pressure detracts to a slight extent from the chemical activity resulting from the high temperatures.

JOINT WORK OF AGENTS OF WEATHERING.

As a matter of observation, we know that the most important chemical reactions which take place in the belt of weathering, as a result of the action of the various agents, are (1) oxidation, (2) carbonation, (3) hydration, (4) solution, (5) deposition.

OXIDATION.

One of the reactions of first importance in the belt of weathering is oxidation. Oxidation is the addition of oxygen to other compounds. The source of the oxygen is the atmosphere, of which it composes 23.12 per cent by weight. This oxygen of the atmosphere acts to some extent directly as a gas, but to a far greater extent through water solutions, and to the greatest extent through water solutions and organisms combined. Of these organisms bacteria are of the greatest consequence, but the molds and fungi are important.

OXIDATION OF ORGANIC COMPOUNDS.

The chief elements oxidized in the organic compounds are carbon, hydrogen, and nitrogen.

Oxidation of carbon and hydrogen.—The most abundant organic compound is cellulose ($nC_6H_{10}O_5$). Other compounds which contain carbon and hydrogen are the proteids, carbohydrates (starch, sugar, etc.), organic acids, fats, etc. The ultimate oxidation products of all these compounds are carbon dioxide and water. This work of oxidation is almost wholly accomplished through the joint work of bacteria and other microbes (such as the fungi), oxygen, and water. The numbers of bacteria engaged in this work are enormous. Estimates by Wollney, Adametz, Koch, Fullus, and others, of the number of bacteria in one gram of soil connected with the formation of carbonic acid gas alone vary from one-half million to one million.

During the oxidation of cellulose a large number of organic acids are produced. Of these organic acids humic acid ($C_{60}H_{54}O_{27}$, Detmer; $C_{24}H_{10}O_6$,

Thenard) is the most important in the soil. Some of the laboratory properties of humic acid are as follows: It is amorphous; it decomposes at 145° C.; after drying, it requires 13,784 parts of boiling water to dissolve it; when undried, it requires 8,333 parts at 6° C. and 625 parts at 100° C. to dissolve it. With humic acid in the soil are various other acids, such as ulmic acid ($C_{18}H_{14}O_6$ or $C_{18}H_{16}O_7$, Berthelot and André), crenic acid ($C_{12}H_{12}O_8$, Mulder), and apocrenic acid ($C_{24}H_{12}O_{12}$, Mulder).[a]

The humic acids are first produced by the oxidation of the cellulose. The other organic acids appear to be produced by further oxidation of the humic acid. Finally, as the process of decomposition continues, humic and the other organic acids by their decomposition are further oxidized and broken up, so that the ultimate products are carbon dioxide and water.

At all stages in the process the acids are active. The humic acid and other organic acids act upon the various inorganic compounds, especially the silicates, forming salts. However, the acids of these salts are broken down to carbonic acid. Also the breaking down of the free humic acid and other organic acids produces carbon dioxide. Therefore the most important result of the decomposition of the cellulose is the production of carbon dioxide. By the process of plant decay carbon dioxide is thus concentrated in large quantities in the belt of weathering—that is, in the place where it can do its most active work. The process of carbonation (explained on pp. 473–480) is consequently largely due to this concentration.

Besides their direct chemical activity, humic and other organic acids have various other important effects in the belt of weathering. As a result of the dark color of humic acid it is an absorbent of the sun's heat. Moreover, it has a higher specific heat than soil, and hence is able to retain a large quantity of heat. Thus, in this way, the presence of humic acid promotes chemical activity. Furthermore, humic acid is hydroscopic, and in sandy soils greatly increases the holding power for water; and it has been noted that the chemical activity in soils is very largely dependent upon the amount of water they hold. Finally, humus in the soils holds ammonia, nitrites, nitrates, and soluble sodium and potassium compounds, in other words, plant foods. These plant foods may be held in some cases as

[a] See also Merrill, George P., Rocks, rock-weathering, and soils, Macmillan Co., New York, 1897, pp. 189–190.

humates or other organic salts These soluble materials thus held by the presence of the humic acid are important plant foods. Therefore, humic acid for many reasons furnishes favorable conditions for further luxuriant plant growth, and these plants again react in a powerful way in promoting the alterations of the belt of weathering.

The process of decomposition of the other carbon- and hydrogen-bearing compounds, aside from cellulose, especially the decomposition of the carbohydrates, is described by Fischer as a fermentation. In this work, as in the decomposition of cellulose, the mold fungi, as well as bacteria, are at work in connection with oxygen and moisture.[a]

While during the history of the earth by far the larger portion of the cellulose formed by organic agencies has been oxidized as above described, from time to time to the present, and in various areas, districts, and regions, this process has been only very partial. As a consequence, the unoxidized cellulose has been buried below later sediments, and thus immense quantities of carbon compounds have been entombed within the earth. This is the main source of the coals, oils, peats, and carbonaceous sediments. It is therefore evident that the total quantity of this entombed organic matter is enormous. By metamorphism of the cellulose these carbon compounds pass into the various forms of coal. After these carbon compounds are formed, as a result of denudation they may again pass into the belt of weathering, and here they are subject to the same oxidizing agencies which are at work upon the original cellulose. But they are now in a more refractory form than the original cellulose, and while the process is doubtless very slow, there is no doubt that the oxidation of the coal and other similar carbon compounds takes place to some extent in the belt of weathering under natural conditions and thus produces carbon dioxide. But, so far as I know, this process has not been studied, and I can make no definite statements in reference to it. It is probably more rapid than is commonly supposed, and the changes are perhaps accelerated by oxidation of sulphides.

Since man began to use coal, peat, and oil, artificial oxidation of the cellulose and the entombed carbon compounds has taken place upon an immense scale. While this method of oxidation of these carbon compounds was trivial until the middle of the eighteenth century, when coal was first applied to the manufacture of iron, it has since that time steadily

[a] Fischer, Alfred, The structure and functions of bacteria, trans. by A. Coppen Jones, Clarendon Press, Oxford, 1900, pp. 107–115.

increased in importance. But it is only during the last half of the nineteenth century that the quantity of carbon compounds artificially oxidized has become of importance. In the year 1899 the amount of coal mined and oxidized amounted to 723,287,454 metric tons. At the beginning of the last decade of the nineteenth century, 1890, the production was only 511,518,358 metric tons.[a] This shows how rapid the increase in the use of coal has been, and therefore a combustion of 1,000,000,000 metric tons a year is probably very conservative as the estimated average for the present century. Taking 1,000,000,000 metric tons as the amount of coal oxidized per annum for the future, and supposing the amount of carbon in this coal to average 80 per cent, the quantity of CO_2 which passes into the atmosphere would be 2,933,333,000 metric tons per annum. This is 0.1233 per cent of the total amount of CO_2 at present in the atmosphere. (See p. 972.) If this rate of consumption of coal were continued eight hundred and twelve years the amount of CO_2 in the atmosphere would be doubled.

It therefore appears probable that within a comparatively short time in the future, as compared with a single geological period, or even an epoch, the amount of CO_2 in one of its great reservoirs, the atmosphere, will be increased to an important extent. From this fact various geological consequences are likely to follow. One of the most important of these is a higher average of temperature for the globe.[b] According to Arrhenius, "if the carbon dioxide is increased 2.5 to 3 times its present value, the temperature in the arctic regions must rise 8° to 9° C. and produce a climate as mild as that of the Eocene period."[c] According to the above computation, the CO_2 would be increased by the oxidation of coal alone to three times its present amount in one thousand six hundred and twenty-four years. Certain it is, if Arrhenius be correct, and the coal supplies of the world are sufficient to meet the demands of man for thousands of years, that a most profound change will take place in the climate of the world.

---

[a] Parker, E. W., Mineral Resources of the United States, 1899; Coal: Twenty-first Ann. Rept. U. S. Geol. Survey, pt. 6, 1901, p. 369.

[b] Chamberlin, T. C., An attempt to frame a working hypothesis of the cause of the Glacial periods on an atmospheric basis: Jour. Geol., vol. 7, 1899, pp. 545–584.

[c] Arrhenius, Svante, On the influence of carbonic acid in the air upon the temperature of the ground: Philos. Mag., 5th ser., vol. 41, 1896, pp. 237–276. Summary in Jour. Geol., vol. 7, pp. 623–625.

A further consequence which would follow from an increase in the amount of CO_2 in the atmosphere and the warmer climate would be a much more abundant and widespread vegetation, and, as pointed out (p. 476), more vegetation means that when oxidized more CO_2 will be concentrated in the soil, and this concentration will lead to an acceleration in the rate of carbonation. Furthermore, the increase in average temperature of the globe will accelerate all other chemical reactions of the belt of weathering. It therefore appears probable that the artificial oxidation of coal will result in some of the most profound and far-reaching geological consequences which are due to the agency of man.

Oxidation of nitrogen.—As already noted, combined nitrogen occurs in various organic compounds, of which the proteids and albuminoids are the more important. The oxidation of this nitrogen, like that of carbon and hydrogen, is a bio-chemical process, being the joint work of microbes, oxygen, and water. Of the microbes, bacteria are by far of the greatest consequence. In the decomposition of the complex nitrogen compounds the nitrogen passes into ammonia, nitrites, nitrates, and, to some extent, free nitrogen. The first stage of the process is the transformation into ammonia. In the case of urea, Fischer gives the reaction as follows:[a]

$$CO(NH_2)_2+2H_2O=CO_3(NH_4)_2$$

The second stage of the process is the transformation of the ammonia into nitrites, and the final stage is the transformation of the nitrites into nitrates. Each of these stages of work is accomplished by certain bacteria which take no part in the other stages. At the same time the nitrogen is oxidized the carbon and hydrogen of the nitrogen compounds are oxidized into carbon dioxide and water, precisely as in the case of cellulose.

So far as the nitrogenous compounds are concerned, the ultimate geological products which remain in the soil are the nitrates, although in the process some small part of the nitrogen is freed and lost, as already noted.[b]

Apparently nitrates are produced on a far vaster scale in the tropical regions than in the temperate regions. Müntz and Marcano state that in

[a] Fischer, cit., p. 103.

[b] Fischer, cit., pp. 98–106. See, also, Conn, H. W., The story of germ life, D. Appleton & Co., New York, 1897, pp. 104, 118; and Aikman, C. M., Manures and manuring, Wm. Blackwood & Sons, London, 1894, pp. 167–170.

places in the valley of the Orinoco the amount of nitrates in the soil amounts to 30 per cent of the mass. The vast amount of these nitrates is doubtless explained by the very great abundance and activity of the bacteria; for it is well known that the high temperature of the Tropics, combined with the high humidity of these regions, is very favorable to the action of bacteria.[a] In this connection Schloessing and Müntz state that the maximum activity of the bacteria is at 30° C., or approximately that of the Tropics.[b]

Much of the combined nitrogen is lost to the belt of weathering in the following ways. In so far as nitrogen is set free by the action of the bacteria and by the passage of the ammonia into the air, it is lost. There are further great losses in the nitrogen compounds by the transportation of the nitrates to the sea by the streams. The quantity of nitrates thus lost has been greatly increased in recent years by the introduction into the streams of sewage containing much combined nitrates. Further, as pointed out by Conn, in so far as the combined nitrogen of the soil is manufactured into powders which are exploded, the combined nitrogen is freed and passes into the atmosphere.[c] The ammonia which passes into the atmosphere may be brought back in part to the soil by the rain. The other losses must, however, be compensated by the synthesis of nitrogen compounds from the nitrogen of the air by bacteria and leguminous plants combined. Until very recently the latter process has preponderated, and the crust of the earth has gained in combined nitrogen. Man in recent times has undoubtedly increased the loss in combined nitrogen, and it is possible, perhaps probable, that the balance is now on the other side, but by care in cultivation, and possibly by manufacture, it will doubtless be possible to continue the process of adding combined nitrogen to the soil faster than it is lost from it.

OXIDATION OF INORGANIC COMPOUNDS.

The most important of the inorganic compounds oxidized are iron and carbon. Other substances subordinate in quantity are also oxidized, but these have small importance from a purely geological point of view. However, from the point of view of ore deposits, and therefore in reference to

[a] Merrill, George P., Rocks, rock-weathering, and soils, Macmillan Co., New York, 1897, p. 372.
[b] Aikman, cit., p. 52.
[c] Conn, cit., p. 106.

the needs of man, the metals in subordinate quantity, such as manganese, copper, zinc, lead, etc., have great importance.

Iron.—Since ore deposits are treated in another place, iron is the only metal which will here be considered. The iron oxidized occurs in the minerals mainly in the form of monoxide. Considerable quantities of it occur as sulphides, and unimportant amounts as arsenides, etc.

Ferrous oxide occurs in the following classes of minerals: Oxides, carbonates, and silicates. Of the oxides, magnetite is the most important. This may be oxidized without hydration into hematite. This change is very well illustrated by the martite ores of the Lake Superior region and by the pseudomorphs of hematite after magnetite in the martite-bearing schists. Simultaneously with the oxidation of magnetite hydration may take place and thus produce hydrated hematite, limonite, or the other hydrated oxides of iron. The change of magnetite to hematite involves an increase in volume of only 2.5 per cent, but where magnetite is changed to limonite the increase in volume is large—64 per cent. Iron in the form of carbonate may occur as pure iron carbonate or as iron carbonate in combination with various proportions of magnesium and calcium. The oxidation of the ferrous iron of the iron carbonate may be accomplished by oxygen and moisture. However, in the soil the process usually takes place with the assistance of bacteria. A certain group of bacteria requires various carbonates for its development.[a] The oxidation of the iron carbonate, whether with or without bacteria, changes it to ferric oxide. Where the oxidation takes place without hydration hematite is formed; where with hydration, limonite, or some of the other oxides of iron. Where bacteria are an agent the common product is limonite. The oxidation of the carbonates involves decarbonation, and on account of this fact there is decrease in volume—in the case of hematite 49 per cent, and in the case of limonite 18 per cent. The transformation of the ferrous oxide of the silicates to ferric oxide, either anhydrous or hydrous, occurs simultaneously with processes of carbonation and hydration of the other bases. So far as there is oxidation and hydration of the iron, this would tend to increase the volume; but the amount of increase can not be calculated independently of the conjoint processes.

---

[a] Lafar, Franz, Technical Mycology, translated by C. T. C. Salter, London, Lippincott, 1898, pp. 360–362.

Of the sulphides of iron, those of marcasite, pyrite, and pyrrhotite are the most important. The oxidation of the iron of these sulphides may be accomplished by oxygen alone, by oxygen and moisture, and finally by oxygen, moisture, and bacteria. With oxygen alone the process is slow; with oxygen and moisture together it is rapid; but oxygen, moisture, and bacteria together furnish the most favorable conditions.

Where oxidation is the only process the compound produced is magnetite or hematite. More commonly, however, hydration occurs simultaneously with the oxidation; and under these circumstances limonite and other hydrated oxides of iron are produced. So far as the oxides are formed, this involves desulphidation.

Sulphur.—At the same time the iron is oxidized the sulphur united with it may also be oxidized. Where the two are oxidized together and remain united the result is to form iron sulphate. Frequently, however, at the time the iron is oxidized the sulphur or some part of it separates as hydrosulphuric, sulphurous, or sulphuric acid. The various reactions resulting in these compounds are given on pages 214–216, and need not here be repeated. By reference to the reactions there written it will be seen that certain of them, as already stated, result in the formation of hydrosulphuric acid. Indeed the reactions producing hydrosulphuric acid are very common during the oxidation of pyrite, marcasite, and pyrrhotite. In a similar manner the oxidation of the monosulphides of the other metals may result in the production of hydrosulphuric acid.

The sulphur of the hydrosulphuric acid may be later oxidized to sulphurous or sulphuric acid. While the oxidation of hydrosulphuric acid may be accomplished by water and oxygen without the assistance of bacteria, often bacteria are the inciting cause of the change. Where hydrosulphuric acid is abundant the hydrogen only is first oxidized and the sulphur stored in the cells of the bacteria, according to the reaction:

$$H_2S+O=H_2O+S$$

But finally the stored sulphur is oxidized by the bacteria to sulphuric acid, which reacts upon the bases present and forms sulphates.[a]

In the transformation of the sulphides the volume change on account of desulphidation produces considerable diminution in volume, provided

[a] Lafar, cit., pp. 370–374.

the oxide of iron is not hydrated—with magnetite, 24 to 39 per cent; but in case both oxidation and hydration occur together there is increase in volume of but 3 per cent in the case of pyrite and 25 per cent in the case of pyrrhotite.

GENERAL STATEMENTS.

It might be inferred from the foregoing statements in reference to the volume relations that, on the average, there is a decrease in volume in oxidation rather than an increase, as one would naturally expect. In support of this view it has been stated that there is generally a decrease in volume in the processes of oxidation of the carbonates and sulphides, since the process of oxidation simultaneously results in decarbonation or desulphidation. However, much more important than the oxidation of iron in the form of carbonate and sulphide is the oxidation of ferrous iron in silicates, and this process does not necessarily involve subtraction of any material. Since it involves addition of oxygen, the result is to produce an increase in volume provided the separated silica or a considerable part of it remains in situ.

As is well known, and as has been pointed out heretofore, the process of oxidation involves great liberation of heat; but the data are not at hand by which the amount of heat liberated can be determined. Concluding in reference to volume and heat relations, it may be said that the process of oxidation perhaps illustrates better than any other the principle that in the zone of katamorphism combinations which take place with the liberation of heat control the reactions rather than the volume relations. Heat is liberated in all the cases of oxidation, and whether there is an increase or decrease of volume is a subordinate factor.

Where the amount of oxygen is sufficient to cause the iron compounds to be transformed to ferric oxide, there are red or yellow soils and subsoils. Excellent illustrations of such regions are the southern Appalachians and the Piedmont Plateau, where the crystalline rocks have deeply weathered. As shown by Russell, the red color of this soil is due to a ferruginous clay containing both ferric oxide and alumina, which incrusts the grains of the rocks.[a] The ferric oxide is produced during the decom-

[a] Russell, I. C., Subaerial decay of rocks, and origin of the red color of certain formations: Bull. U. S. Geol. Survey No. 52, 1889, pp. 14–15.

position of the parent rocks. Another illustrative region, described by Hayes, is that of Nicaragua east of the continental divide. The red color in this belt is from 3 to 10 meters deep.[a] Both of these regions are those of rather high temperature and abundant precipitation throughout the year, and therefore abundant vegetation. They therefore well illustrate the conditions under which decomposition of the rocks, including oxidation, takes place. The very abundant transpiration by the luxuriant foliage (see p. 422) doubtless is a very important factor in preventing the soil from becoming saturated with moisture for any considerable period, and thus the conditions for oxidation are maintained.

One would suppose that in the soil, where oxidation of organic and inorganic matter is active, the amount of oxygen in the gases would be less than in the atmosphere, and observations by Fleck, Letts and Blake and others confirm this conclusion. The amount in the atmosphere is 20.92 per cent by volume, whereas Fleck, as cited by Letts and Blake, finds that at a depth of 2 meters the minimum is 16.33 per cent and the maximum 19.39 per cent; at 4 meters the minimum is 15.67 per cent and the maximum 16.79 per cent; at 6 meters the minimum is 14.94 per cent and the maximum 14.85 per cent.[b] These last numbers are only a little more than two-thirds the full amount of oxygen of the atmosphere. It appears that as depth increases, and therefore as the air of the soil is further removed from its source of supply—the oxygen of the atmosphere—there is a steadily decreasing amount, and this fact must be explained by the consumption of oxygen by the oxidation of organic and inorganic matter.

In some cases the amount of oxygen is little more than half as great as that in the air. The deficiency varies directly, although not in simple ratio, with rapidity of oxidation and with the depth below the surface where the process takes place.[c]

While oxidation is the normal process in the belt of weathering, under certain conditions deoxidation may take place. Under such circumstances gray or white soils and subsoils are formed. This is illustrated by the western division of Nicaragua, where Hayes states that the clays are blue,

---

[a] Hayes, C. W., Report of the Nicaragua Canal Commission, Appendix II, Geologic Report, 1899, pp. 128–129.

[b] The last number must be a misprint. Letts, E. A., and Blake, R. F., The carbonic anhydride of the atmosphere: Scientific Proc. Royal Dublin Soc., vol. 9, new ser., pt. 2, p. 215.

[c] Aikman, C. M., Manures and manuring, Blackwood & Sons, London, 1894, p. 100.

the iron being in the ferrous form.[a] This is a region of less humidity than the eastern region, and here dry seasons alternate with very wet seasons. According to Hayes, during the dry season each year the soil cracks deeply, and a large amount of organic material falls into these cracks. During the wet season the soil swells and fills the cracks, and the organic matter becomes incorporated with the soil. This material acts as a reducing agent and prevents the further oxidation of the iron, or reduces any part of the iron oxide which has become ferric oxide to the ferrous state.

While this explanation is plausible, it seems incomplete. In the eastern division the soil is continuously in contact with numerous dead and dying roots of the abundant vegetation, and the question naturally arises whether the difference is not due to saturation of the soil of the western division, as explained below, the cracks being utilized by the water.

Deoxidation of the iron may occur in regions where the water of the soil is so abundant as to approach saturation, and plants are abundant. Under such conditions the large amount of oxygen required to decompose the plants is not able to enter from the air with sufficient rapidity, and hence the oxidation of the plants abstracts oxygen from ferric oxide, and this reduces the iron to the ferrous condition. This reduction of ferric salts results from the demands of the abundant oxidizing bacteria for oxygen where organic matter is being rapidly decomposed. Consequently the process of deoxidation of iron compounds commonly takes place only by the oxidation of organic constituents. So far as the inorganic constituent is concerned, there is absolute loss of oxygen by the process.

Examples of deoxidation of iron compounds are furnished by the so-called cumulous deposits, where abundant vegetation near the water level accumulates and does not completely decay. Instances of such deposits are the sphagnum mosses of marshes, bogs, lakes, and the margin of the ocean, which result in the accumulation of peat; and the swamps, for example, cedar, spruce, mangrove, etc. Probably the same conditions obtained in the past, especially at the coal-forming periods, for the underclays of coal beds are almost always gray or white, the iron having been almost completely reduced to the ferrous form.

The iron reduced to the ferrous condition and that already in the ferrous condition in the silicates is in the most favorable form to unite

[a] Hayes, cit., pp. 130–132.

with carbon dioxide, as explained under "Carbonation;" and thus may be produced a great quantity of iron carbonate, which may join the sea of ground water and furnish the material for chalybeate springs and for siderite deposits, as explained on pages 824–829. The clay ironstones and the siderite, often associated with the coal beds and frequently in the coal itself, are illustrations of such siderite deposits. Thus the association of deposits of iron carbonate with coal deposits is explained, and also—as developed on pages 842–846—there is in this iron carbonate thus formed the source from which other iron-ore bodies are concentrated.

Another example of deoxidation is furnished by the nitrates, which may be reduced to nitrites, or even to free nitrogen when the conditions of the belt of weathering are those of abundant vegetation and very high humidity.[a] The reduction of the nitrites is effected by definite bacteria. It is highly probable that the oxygen abstracted in the deoxidation of nitrates, like that abstracted from ferric iron, is used by the oxidizing bacteria in decomposing the organic matter.

Under conditions similar to those in which ferric iron is reduced to the ferrous form and nitrates are reduced, sulphates may also be reduced to sulphides. This is usually accomplished mainly by organic material where abundant to serve as a reducing agent; but also in this reduction, as in various other processes, bacteria may play a part.[b]

Finally, where the moisture is too abundant the oxidation of the plants themselves is greatly delayed, and may be permanently stayed. The best illustration of the lag in decay of plants and deoxidation of the ferric salts, nitrates, and sulphates is found in the marshes where water entirely covers the soil, and thus makes the oxidation very slow indeed. Where the plants fall below the surface of the water the plant decay may be very partial, and hence there may be produced peat or coal beds. But in this connection it should be recalled that where, as a result of great humidity, the decay of plants is slow and deoxidation takes place the conditions approach those of the belt of cementation. In swamp areas the thickness of the belt of weathering is practically reduced to zero; the roots of vegetation reach below the level of ground water, and under these circumstances the reactions which take place in connection with organic matter are those of the belt of cementation rather than those of the belt of weathering.

---

[a] Aikman, cit., pp. 177–178.

[b] Lafar, cit., pp. 363 et seq.

It has been shown that in the belt of cementation oxidation is much less prevalent than in the belt of weathering, and indeed that, on the whole, deoxidation, especially where organic material is prevalent, is the rule. Therefore, the reversal of the ordinary process of oxidation in the belt of weathering usually takes place only where this belt is grading into or is under conditions which are approaching those of the belt of cementation and below.

It has already been stated that the direct source of the oxygen for the process of oxidation is the atmosphere. It is apparent from the foregoing that a vast amount of oxygen is now being demanded for this process, and the amount of oxygen which has thus been consumed during geological time is beyond computation. But it will be seen under "The zone of anamorphism" that there are also processes which restore oxygen to the atmosphere. Which of these processes, oxidation or deoxidation, is, on the whole, preponderant and what are the possible sources of supply for oxygen can best be considered after all the reactions in each of the belts are considered, and therefore this subject is taken up in Chapter XI.

CARBONATION.

The process of carbonation may be defined as the union of carbonic acid with bases, forming carbonates. Since the carbonates are not known as original minerals in the igneous rocks, we must look in other directions for the source of the carbon dioxide for the process of carbonation. The immediate reservoir for this carbon dioxide is undoubtedly the atmosphere, but the amount in the atmosphere is very small, only 0.045 per cent by weight, and the quantity now in the atmosphere is, as will be seen subsequently, insignificant as compared with that which must have been abstracted from the atmosphere during past geological ages by the process of carbonation. Either the atmosphere must have once contained vastly more carbon dioxide than at present, or else it must have been continuously replenished in this compound, or partly both. These questions can be best discussed after the reactions of both the zone of katamorphism and the zone of anamorphism have been considered, and their consideration is deferred to Chapter XI.

It has been explained that from the atmospheric reservoir the plants absorb carbon dioxide, reduce it, and build it into their bodies. Further-

more, it has been seen that oxidation of organic materials by bacteria and oxygen in the belt of weathering produces carbon dioxide abundantly. This process, therefore, concentrates in the upper part of the belt of weathering a large amount of carbon dioxide, and this carbon dioxide is available for the process of carbonation. The fact of the concentration of carbon dioxide in the upper part of the crust of the earth was noted by Bischof many years ago. In the waters of his laboratory well at Bonn he found three times as much carbonate of lime as in the Rhine near by Also, free carbonic acid often collects above the water of wells. Facts like these, and the large amounts of carbonic acids in mines Bischof explained by the oxidation of organic matter, including coal.[a]

The importance of the process of concentration of carbon dioxide in the belt of weathering through the oxidation of organisms can be appreciated only by comparing the amount of this material in the atmosphere with the amount in the gases of the belt of weathering where vegetation is present.

The amount of carbon dioxide in rain water, according to Fischer, varies from 0.22 to 0.45 per cent of the volume of the water, or only 0.00044 and 0.00089 per cent by weight.[b]

It has already been noted that the amount of the carbon dioxide in the atmosphere by weight is about 4.5 in 10,000. The amount present in gases of the soil is far greater than this, as shown by the following table by Boussingault and Lewy:[c]

Table showing the amount of carbon dioxide in the air of belt of weathering.

	CO_2 in 10,000 parts by weight.
Air from sandy subsoil of forest	38
Air from loamy subsoil of forest	124
Air from surface soil of forest	130
Air from surface soil of vineyard	146
Air from pasture soil	270
Air from soil rich in humus	543

[a] Bischof, Gustav, Elements of chemical and physical geology, Harrison & Sons, London, 1854, vol. 1, p. 239. (Translated by Paul and Drummond.)

[b] Merrill, George P., Rocks, rock-weathering, and soils, Macmillan Co., New York, 1897, p. 179.

[c] Merrill, cit., p. 178.

Fleck, as cited by Letts and Blake, found in the soil at a depth of 6 meters by volume a minimum amount of carbon dioxide of 4.22 per cent, and a maximum amount of 7.96 per cent; at 4 meters, a minimum amount of 4.11 per cent and a maximum amount of 5.56 per cent; at 2 meters, a minimum amount of 2.99 per cent and a maximum amount of 2.91 per cent (the last number must be a misprint).[a]

These figures show that the amount of carbon dioxide in the ordinary air is insignificant in comparison with the amount in soils in regions of luxuriant vegetation. In such regions the carbon dioxide is from thirty to more than one hundred times more abundant than in the atmosphere. This large amount is mainly furnished by the decomposition of vegetation, although, as shown by Briggs, even dry soils have the power to absorb carbon dioxide from the atmosphere.[b]

The process of carbonation is dominantly accomplished by the substitution of carbonic for silicic acid. The negative side of this process is desilication. To a very small extent carbonation is accomplished by the substitution of carbonic acid for other acids—for instance, phosphoric acid. Also carbonates are produced on a considerable scale by the union of carbon dioxide with the oxides which were not united with other acids, as, for instance, ferrous oxide in magnetite.

Mueller has experimentally ascertained that carbon dioxide in water at ordinary temperatures and pressures is capable of attacking many minerals. Of the oxides, he experimented with magnetite; of the silicates, he experimented with orthoclase, oligoclase, hornblende, olivine, serpentine, and muscovite. He also experimented upon a number of phosphates, including apatite. While all of the silicates experimented with were attacked to some extent, there was great variation in the rate of action. For instance, orthoclase is attacked more readily than oligoclase; hornblende and serpentine are attacked more rapidly than the feldspars, and olivine is the most readily attacked of all the silicates tested. The process of carbonation formed carbonates of sodium, potassium, calcium, magnesium, and iron. Alumina also went into solution. The liberated silica partly went into solution, but partly also separated as quartz. Magnetite was the most

[a] Letts, E. A., and Blake, R. F., The carbonic anhydride of the atmosphere: Sci. Proc. Royal Dublin Soc., vol. 9, pt. 2, 1900, p. 215.

[b] Cameron, Frank K., Soil solutions, their nature and functions, and the classification of alkali lands: Bull. U. S. Dept. Agric. No. 17, 1901, p. 17.

resistant of all the minerals and rocks tested. Apatite was found to be as readily soluble as the more soluble silicates. Perhaps one of the most interesting results in reference to the silicates is the comparative readiness with which the hydrous silicate, serpentine, is attacked. From this fact Mueller makes the point that this silicate does not represent an end product of alteration.[a]

Johnstone later experimented upon the micas, including muscovite, biotite, and lepidomelane, and found that they are attacked by water solutions of carbon dioxide.[b] As one would expect from the above reactions, Struve[c] found that water containing carbon dioxide at ordinary pressure attacked basalt, phonolite, gneiss, granite, clay slate, and porphyry.

Combining the experimental fact that carbon-dioxide solutions decompose the silicates and the observed fact of the abundance of CO_2 where vegetation is plentiful, one would expect that the process of carbonation would be more rapid in regions of abundant vegetation than elsewhere. Belt many years ago made observations which confirm this expectation. He says that the decomposition of rocks in tropical America is largely confined to the forest regions, and ascribes it to the action of water charged with acids derived from the decomposing vegetation.[d] Where vegetable matter is abundant it has also been observed that the amount of dissolved silica contained in underground water is much greater than where vegetation is sparse or absent.[e] This observation is direct evidence that the reactions of carbonation and desilication are correlative, and are very largely due to the concentration of carbon dioxide in the belt of weathering by the oxidation of organic matter.

Since the reaction of carbon dioxide upon the silicates and other compounds forms carbonates, in a soil there may be present both sedimentary and secondary carbonates. Now, it has been shown experimentally by Bischof that the alkaline carbonates are capable of decomposing the silicates at

---

[a] Mueller, Richard, Untersuchungen ueber die Einwirkung des kohlensäurehaltigen Wassers auf einige Mineralien und Gesteine: Tschermak's mineral. Mittheil., vol. 7, 1877, pp. 25–48, especially pp. 39, 46–48. See Merrill, G. P., Rocks, rock-weathering, and soils; Macmillan Co., New York, 1897, pp. 192–193.

[b] Johnstone, A., On the action of pure water and of water saturated with carbonic-acid gas on the minerals of the mica family: Quart. Jour. Geol. Soc. London, vol. 45, 1889, pp. 363–368.

[c] Struve, F. A. A., Ueber die Nachbildung der natürlichen Heilquellen, Pogg. Ann. vol. 7, pp. 341–372–429–450.

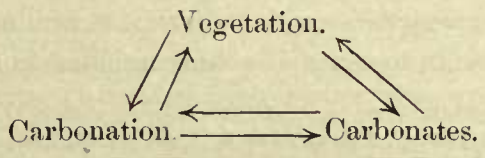
[d] Belt, Thomas, The naturalist in Nicaragua, 1874; cited in Merrill, p. 175.

[e] Hunt, T. Sterry, Chemical and geological essays, 1875, pp. 149–152.

ordinary temperatures and pressures.[a] A great variety of silicates were thus decomposed. The alkaline silicates and carbonates of sodium, potassium, calcium, magnesium, and iron were formed. Not only do the alkaline carbonates decompose silicates in the belt of weathering, but other carbonates accomplish the same result. This has been shown by observations on the alterations in the soil by Hilgard.[b] Of these other carbonates, that of calcium has been found to be the most important. Hilgard states that the decomposition of the silicates is much more active in calcareous soils than in noncalcareous soils that are otherwise similar. He says "this is seen when we contrast the analyses of calcareous clay soils of the humid region with the corresponding noncalcareous ones of the same. In the former the proportions of dissolved silica and alumina are almost invariably much greater than in the latter, so far as such comparisons are practicable without assured absolute identity of materials."[c]

Since the carbonate sediments are mainly or solely produced by the process of carbonation of the silicates of an earlier period, Hilgard's statement is equivalent to saying that the process of carbonation to-day is promoted by the carbonation of past geological ages.

It is well known that soils containing carbonates are fertile, and therefore are favorable to abundant vegetation. This is well illustrated by the limestone soils. As already seen, vegetation promotes carbonation, and thus produces carbonates. It therefore appears that there is constant action and reaction through vegetation and carbonation in promoting the process of carbonation. Vegetation results in the process of carbonation, and this produces the carbonates. Carbonates in turn result in further carbonation and furnish favorable conditions for vegetation. Carbonation provides carbonates, and therefore promotes vegetation. The relations of the three may be represented by the following diagram, the arrows indicating the directions of action and reaction.



[a] Bischof, G., Elements of chemical and physical geology, translated by B. H. Paul and J. Drummond, Harrison & Sons, London, 1854, vol. 1, pp. 8–11.

[b] Hilgard, E. W., Report on the relations of soil to climate: Bull. Weather Bureau, U. S. Dept. of Agric., No. 3, 1892, pp. 36–38; cited, Merrill, p. 371.

[c] Hilgard, cit., p. 37.

The process of carbonation with the liberation of silicic acid is continuous, cumulative, and takes place on a vast scale. Notwithstanding this, there is, as already seen (p. 474), only a comparatively small amount of carbon dioxide in the belt of weathering at any one time—from 38 to 500 parts in 10,000. Carbonates may be present; if so, they represent the action of earlier carbon dioxide. The continuous process of carbonation may be understood when the law of mass action and the time factor are considered. Under the law of mass action an acid anywhere existing will unite with some of the bases present. The compounds thus produced are in part transported elsewhere by underground and overground drainage. The carbon dioxide used is resupplied by the oxidation of organic material, and thus the reacting agent continues its work; and so the process goes on unceasingly through geological time.

While this cumulative process goes on without cessation in the humid regions where the carbonates are largely removed by solution, in the semi-arid and arid regions the carbonates, especially the alkaline carbonates, may become so abundant in the soil as to be unfavorable to vegetation, and thus check the process. (See p. 543.) Where the alkalies, especially sodium carbonate, exceed a certain very small amount, vegetation can not exist, and the region becomes a desert.[a]

"The amount of soluble salts which plants can stand depends upon the character of the salt, the character of the soil, and the kind of plant. Hilgard states that few plants can bear as much as 0.1 of 1 per cent of sodium carbonate, or about 3,500 pounds per acre to a depth of 1 foot [about 3.9 kg. per sq. meter to depth of 30 cm.]; of sodium chloride, about 0.25 per cent; and of sodium sulphate most plants can grow with 0.45 to 0.50 per cent present, and are affected by even less salts in the sandy lands than on heavy clay or gumbo lands."[b]

The process of carbonation with desilication just described may take place without other reactions with a number of minerals. (See p. 396.) The change involves an increase in volume ranging from about 13 per cent

[a] Means, Thos. H., and Gardner, Frank D., A soil survey of the Pecos Valley, New Mexico: Field operations of Div. of Soils, U. S. Dept. of Agric., 1899, No. 64, 1900, pp. 53–58.

[b] Whitney, Milton, and Means, Thos. H., The alkali soils of the Yellowstone Valley: Bull. Div. of Soils, U. S. Dept. of Agric., No. 14, 1898, p. 10.

to over 50 per cent. But carbonation with or without desilication occurs on far the most extensive scale in connection with hydration. When the great majority of the abundant silicate minerals are carbonated they are also hydrated. (See pp. 397–399.) Finally carbonation with desilication occurs rather extensively in connection with both oxidation and hydration. (See p. 399.) In all these combinations, provided all the compounds formed remain as solids, there is an increase in volume. This increase rarely falls below 5 per cent; it runs as high as 75 per cent, or even higher, but the more common range is between 15 and 50 per cent. It is well known that the processes carbonation, carbonation combined with hydration or oxidation, and carbonation combined with both hydration and oxidation, liberate much heat, but the data are not at hand from which the amount can be calculated.

The process of carbonation just considered is one of paramount importance in the belt of weathering. Although the process is not so extensive as hydration, if one were to pick out a single chemical process especially characteristic of this belt and of great significance in geology it would be carbonation. Carbonation has continued through all geological time since land areas first arose above the sea. Moreover, it has continued in all the land areas of the globe; but the process is very slow in the frigid zones, becomes of importance in the temperate zones, and is of great consequence in the torrid regions. In the warm regions the process is rapid in proportion as there is high humidity and consequently abundant life. In the arid regions carbonation is comparatively slow.

There is no reason to suppose that the carbonates existed as original rocks or as original minerals of the igneous rocks. If this be so, all the carbonate formations which now exist and which have existed at any time in the past have been produced by carbonation. The precipitation of carbonates in the sea is accomplished largely through organic agencies. These carbonates are essential to the existence of great classes of sea animals, and certain it is had not these carbonates formed by the process of carbonation and been contributed to the ocean, the evolution of life upon the globe would have followed entirely different lines from those that have been followed.

Notwithstanding the vast scale and dominant importance of the process of carbonation, it is mainly accomplished, as has already been seen, through the small amount of carbon dioxide continuously concentrated in the belt of weathering by means of organic material. It is therefore clear that a very slow but continuous action, extending over the globe throughout geological time, has produced stupendous results. But the positive side of the process of carbonation is of scarcely less importance than the negative side. It has been pointed out that carbonation largely takes place through the decomposition of the silicates or by desilication. The silica set free, as already noted, largely separates as colloidal silicic acid. The amount of silica thus liberated approximates to the molecular equivalent of the carbon dioxide which unites with the bases combined with silica; or, since the molecular weights of carbon dioxide and silica are 44 and 60.4, there is about one and one-third times as much silica released from the silicates as there is carbon dioxide combined in the carbonates. The stupendous results of the process of carbonation are therefore matched by the results of the process of desilication. As will be seen subsequently, while a portion of the silica of the colloidal silicic acid is precipitated in the belt of weathering, probably by far the greater part of it is carried by the ground waters to the belt of cementation, and is there largely precipitated.

While carbonation, with correlative desilication, is of such fundamental importance in the belt of weathering, under exceptional conditions silication may occur. Where silica is very abundant and in a readily soluble form, the law of mass action may be so effective as to result in the formation of abundant silicates rather than carbonates. This has not been observed as a general process in the belt of weathering, doubtless because of the lack of close observation. However, in many cases in ore deposits above the level of ground water the silicates of the metals are formed. So far as I know, this is better illustrated in the lead and zinc district of Missouri than elsewhere. Here silica as chert, partly amorphous, is very abundant. The zinc was originally in the form of sulphide. As the level of ground water descended owing to denudation, and the sulphide arose into the belt of weathering, the zinc sulphide was decomposed, the zinc being oxidized. Simultaneously with this process it united, upon a somewhat extensive scale, with the silica, producing silicate of zinc.

HYDRATION AND DEHYDRATION.

By hydration is meant the union of water with chemical compounds, thus producing hydrous minerals. The water for hydration is derived mainly from the hydrosphere. Hydration stands as the most extensive reaction in the belt of weathering. In its importance in this belt as a geological process it is second only to carbonation. Indeed, it has been supposed by some geologists that hydration is the dominant reaction of the belt of weathering, the process of carbonation being wholly ignored. The list of important hydrous minerals formed comprises many silicates and oxides and some carbonates, sulphates, etc.

As a matter of observation, all of the so-called anhydrous silicate minerals of the igneous, sedimentary, and metamorphic rocks which have long remained in the belt of weathering are shown by analysis to have become more or less hydrated. But more important than this, the new minerals which develop in the belt of weathering are usually strongly hydrated. Of these in the silicate class the kaolin, serpentine-talc, chlorite, and zeolite groups are examples. Of the oxides the most important are those of aluminum and iron, the former occurring as gibbsite or diaspore; and the latter commonly as limonite, but not infrequently as göthite or some other hydrated oxide.

In many cases in the dense rocks hydration goes on to a certain stage and then ceases or at least becomes very slow. This is due to the fact that the process of hydration involves expansion of volume and therefore makes it necessary that the superjacent material be elevated if the process continues. Such partly hydrated rocks below the surface when brought to the surface, and therefore relieved from pressure, may continue to rapidly hydrate nearly or quite to the completion of the process with great expansion of volume. In many cases the process is so rapid that the term slaking is applicable. This slaking has been observed by Merrill in the granitic rocks of the District of Columbia,[a] and by Derby in the sedimentary rocks from railway cuttings of Brazil.[b] In both of these places the rocks when exposed at the surface soon break into powder, although in position they are perhaps so strong as to require blasting. These facts make it clear that the process of hydration is largely dependent upon the pore space in the rocks. Where

[a] Merrill, George P., Rocks, rock-weathering, and soils, Macmillan Co., New York, 1897, p. 188.
[b] Derby, O. A., Decomposition of rocks in Brazil: Jour. Geol., vol. 4, 1896, pp. 529–540.

there is large pore space and abundant room, so that hydration may take place without lifting the rocks, it is probable that with sufficient time the process may go on to completion in all parts of the belt of weathering. However, in proportion as the rocks are dense and contain small pore space the process of hydration at an early stage is likely to be retarded or altogether stayed, because of the necessity demanded for more space and because the chemical affinity of rocks for water is not strong enough, at least in the later stages of the process, to overcome considerable pressure.

While hydration is the rule for the belt of weathering, in regions in which the temperature is high and which are not continuously humid dehydration may take place. Dehydration probably occurs on the largest scale in regions of high temperature in which dry and wet seasons alternate. During the wet season hydration occurs, and at the dry times dehydration occurs. This process is well illustrated by iron. As is well known, ferric iron in the belt of weathering is ordinarily hydrous, and this gives a yellow color. In regions of high temperature where the humidity is low for at least a portion of the year the soil is likely to be red, the iron being in the form of hematite rather than göthite or limonite. Such regions are illustrated by the Desert Ranges of southern California, in which dark red is the dominant color. But dehydration also takes place to some extent in such humid regions as the southern Appalachians. Crosby, Dana, and Russell attribute to dehydration the bright-red color of the surface soil in this region as compared with the less brilliant color of the subsoil.[a] This region, although one of large precipitation, is apt to be dry in late summer and autumn, the season when conditions are favorable to dehydration. In the subsoil the process is naturally less marked. The dehydration of iron is well known, because the process involves a change of color. Under the conditions in which dehydration of iron takes place, it is certain that many of the other hydrates which form in the belt of weathering are also dehydrated to a greater or less extent. It is well known that the process of dehydration of many minerals begins at temperatures lower than 110° C. Indeed, it is certain that the dehydration of limonite and other hydrous oxides of iron begins as low as 100° C., and that if this temperature be maintained even during the insignificant time in which an experiment is

[a] Merrill, cit., p. 385.

carried on in a laboratory, dehydration is very appreciable.[a] These temperatures are not reached under natural conditions, but in hot regions where water is not plentiful it is probable that partial dehydration of such compounds as the zeolites, colloidal silicic acid, etc., takes place on a considerable scale. Doubtless the process in reference to these minerals has not been commented upon because ordinarily there is no accompanying change in color. To illustrate, the table on pages 375–394 shows that aluminum hydroxide, as gibbsite and diaspore, forms on a vastly greater scale in the belt of weathering than ferric hydroxide. It is highly probable that, under the same conditions in which dehydration of iron occurs, dehydration of aluminum hydroxide also takes place to some extent. The same statements may be made in reference to the other hydrous minerals which lose their water or a part of it at a low temperature, as, for instance, the zeolites.

It has already been stated that hydration is the most extensive reaction of the belt of weathering. This is at once found by reference to the classified tables of alterations, page 402. It is there seen that a number of the important oxides and many of the more important silicates may be altered by simple hydration. The process of hydration, as explained in Chapter IV, from a physical-chemical point of view, involves expansion of volume and the liberation of heat. The amount of heat liberated is great, as shown in Chapter V. Whether hydration occurs alone or occurs combined with the other processes, there is an increase in volume. In simple hydration the volume increase ranges from a very small per cent to as high as 160 per cent, as in the alteration of corundum to gibbsite. Commonly the increase in volume is less than 50 per cent. The quantity of heat liberated in the process of hydration is great, but the average amount can not be quantitatively stated.

OXIDATION, CARBONATION, AND HYDRATION.

As already noted, oxidation, carbonation, and hydration may each take place separately, but commonly two or three of these processes are simultaneously at work on the same rocks, and even on the individual mineral particles. No average can be given as to the amount of increase

[a] Leith, C. K., The Mesabi iron-bearing district of Minnesota: Mon. U. S. Geol. Survey, vol. 43, 1903, p. 262.

in volume as a consequence of the combination of these three reactions, but doubtless in most cases the increase in volume, where the processes are complete, is 15 to 50 per cent or even more.

It is of importance to note that the oxygen, carbon dioxide, and water added to the rocks in the belt of weathering are not directly derived from other rock materials, but are in large measure derived from the atmosphere and hydrosphere. As already noted, the oxygen is directly derived from the atmosphere; the carbon dioxide comes from the atmosphere mainly through the intermediary action of vegetation and other organic matter, and water is derived directly or indirectly from the hydrosphere. The depletion of the atmosphere and hydrosphere in oxygen, carbon dioxide, and water is continuous, and through geological ages would doubtless seriously encroach upon the supplies of these materials were it not for the compensatory reversing reactions largely occurring in the zone of anamorphism. (See pp. 366–369.)

SOLUTION.

Concurrently with the processes of oxidation, carbonation, and hydration, the underground waters of the belt of weathering take compounds into solution. The process of solution is not only concurrent with these other processes, but is promoted by them. This follows from the fact that the dominant processes of carbonation and hydration transform the compounds into more soluble forms. The change of ferrous to ferric iron by oxidation has a reverse effect, but the quantitative value of this reaction is small compared with that of carbonation and hydration.

It has already been explained that all natural compounds are soluble in pure water, but the solution would be slow if this were the only solvent. It has been seen that in the underground solutions of the belt of weathering there are continually produced organic acids, carbonic acid, nitric acid, sulphuric acid, and hydrosulphuric acid. These produce corresponding salts—carbonates, nitrates, sulphates, and sulphides. Also the presence of these salts favors solution. Besides these salts chlorides are present. The active acids of the solutions unite with the bases of the minerals. But in this process the acids with which the bases were united in the minerals are displaced, and these acids may also pass into the solutions and become active constituents. The oxygen, carbonic acid, nitric acid, sulphuric acid, and hydrosulphuric

acid have been accounted for by processes in the belt of weathering. But the source of the hydrochloric acid, producing the chlorides, has not been explained. This subject is considered on pages 789–790.

The amounts of the compounds which are taken into solution by ground waters depend very largely upon the number and amounts of the above active chemical agents or solvents. Also the amounts of the compounds which are taken into solution depend upon the relative proportions of the elements present, and the manner in which they are compounded. If all the important bases occurring in the rock-making minerals were equally abundant the stronger bases would be taken into solution to a larger extent than the weaker bases. Therefore there would be dissolved more sodium and potassium than calcium and magnesium, more calcium or magnesium than iron, more iron than aluminum. And as a matter of fact, the percentages of the compounds dissolved are in this order. But the amount of alkalies in the rocks is much less than that of the alkaline earths, iron, or aluminum, and consequently the total amount of the former elements dissolved may be less than the latter—indeed, is commonly much less than the amount of the dissolved alkaline earths. Further, the greater the proportion of bases present as compared with the acids—i. e., the more basic the compounds—the more readily the minerals are decomposed and the greater the amount of bases which are dissolved. If the acids were present in equal quantity there would be dissolved a greater amount of the salts of the stronger acids than of the weaker acids. Thus there would be a greater quantity of sulphates, nitrates, and chlorides than of the carbonates. Since, however, in the solutions carbonic acid is so much more plentiful than any other active acid, carbonates greatly predominate. The only acid in solution which can be compared with carbonic acid in abundance is silicic acid, produced by the decomposition of the silicates. However, the liberated silicic acid, as explained on pages 115, 176, separates in a colloidal state, and in that form is exceedingly inactive and, notwithstanding its great quantity, does comparatively little work. The great power of the weak acid, carbonic, in the solutions shows that the law of mass action is of great consequence in the relative amounts of the compounds formed and taken into solution.

The above general statements are very well illustrated by T. Mellard Reade's estimate of the amount of salts which are abstracted from each

square mile of area.[a] He calculates that throughout the entire globe there is removed annually in solution 96 tons (about 86 tonneaus) of material per square mile, which he divides as follows: Calcium carbonate, 50 tons (45 tonneaus); calcium sulphate, 20 tons (18 tonneaus); sodium chloride, 8 tons (7.2 tonneaus); silica, 7 tons (6.3 tonneaus); alkaline carbonates and sulphates, 6 tons (5.4 tonneaus); magnesium carbonate, 4 tons (3.6 tonneaus); oxide of iron, 1 ton (0.9 tonneaus). The order of the larger of these amounts is much what one would expect. The strong, abundant base, calcium, is largely united with the weak abundant acid, carbonic. The strong acids, such as sulphuric and hydrochloric, are largely united with the alkaline metals, sodium and potassium, but a residuum is left over which is supposed to be united with the calcium.

We now know that in solutions all the bases are united with all the acids except so far as dissociation occurs, according to the various factors of strength, mass, and solubility, and we can see that it would have been better to have estimated the various compounds as oxides or elements rather than as salts. But it would still be true that the most abundant salt is calcium carbonate, that that standing next in abundance is probably calcium sulphate, and that those standing next in abundance are the alkaline sulphates and chlorides.

We conclude from the foregoing that in the belt of weathering all the elements in the minerals are being dissolved all the time, but with greatly varying rates, depending upon the strength and abundance of the active compounds in solution and upon the solubility of the various minerals upon which the solvents are acting. While the more readily soluble substances are dissolved many times more rapidly than those which are usually spoken of as insoluble, even those substances which are least soluble may be taken into solution on a large scale. For instance, silica in the form of quartz is regarded as exceedingly insoluble, yet it is certain that in the iron-bearing formations of the Lake Superior region quartz has been dissolved on an enormous scale. Also the evidence is conclusive that such extremely refractory substances as hematite and limonite are dissolved. (See pp. 548–549.) While all minerals in the belt of weathering are soluble, after a sufficient length of time the constituents remaining undissolved are, of course, those which are relatively insoluble.

---

[a] Reade, T. Mellard, Chemical denudation in relation to geological time. Also Merrill, cit., p. 194.

Consequent upon these various reactions, combined with solution, material is continuously abstracted from the belt of weathering, and thus the openings tend to increase in size. This does not appear in the case of the unconsolidated materials at the surface, for gravity brings the particles together as fast as material is dissolved; but in the rocks which have sufficient strength to hold together, the openings are often numerous and large, and constitute a considerable percentage of the volume of the rocks. The best illustrations of rocks with large openings are the limestones, which, above the level of ground water, are commonly intersected with numerous open joints, are often porous throughout, and not infrequently contain caves. On account of the continuous abstraction of material by the ground waters the belt of weathering might be called the belt of solution.

DEPOSITION.

Later it will be seen that concurrently with solution, favored by it and in direct proportion to it, deposition is constantly going on. Thus it will be seen that the substances dissolved in greatest quantity are those deposited in greatest quantity. As just noted, in limestone regions solution takes place on an enormous scale. But while this is going on deposition of $CaCO_3$ is occurring on a large scale; for instance, in caves travertine, stalactites, and stalagmites are forming. Where evaporation is not easy, solution will be the rule; where evaporation is easy, deposition. Thus a cave may be simultaneously enlarged at the bottom and decreased in size at the top. Solution and deposition are correlative processes, but in the belt of weathering the first is dominant. The absolute amount abstracted, estimated by Reade at 96 tons per annum per square mile, represents the difference between the results of solution and deposition.

GENERAL STATEMENTS.

On the preceding pages it has been seen that the processes of oxidation, carbonation, hydration, and solution are characteristic of the belt of weathering, and that all take place on a great scale. However, it has also been seen that to some extent the reverse of these processes—deoxidation, silication, dehydration and deposition—also occur. This is what one would expect from the laws of physical chemistry. All chemical reactions are reversible; and while the first set of the above processes greatly

dominates over the reverse set, all the above sets of reactions take place on an important scale in the belt of weathering, although the belt is characterized by the one set rather than the other.

CONTACT METAMORPHISM.

Contact metamorphism is a term used to cover the mutual effects of intrusive and intruded rocks. The effect upon the intruded rocks is known as exomorphic and that upon the intrusive rock as endomorphic. The first is of greater consequence. In considering the exomorphic effect, ordinarily there has been no well-defined attempt to estimate the relative importance of the direct and indirect action of the igneous rocks. The direct effect is due to the heating of the intruded by the intrusive rock. The indirect effect is due to the increased activity of the gaseous and liquid solutions caused by the intrusive rocks.

The gaseous and liquid solutions adjacent to igneous rocks differ from ordinary solutions in two respects. First, at the time of the crystallization of magmas, gases and liquids emanate from the igneous rocks. The chief constituent of these emanations is, of course, water, but associated with the water are other compounds. By the circulation of the gaseous and liquid solutions the material emanating from the igneous rocks may pass into the surrounding rocks. A second and still more important indirect effect is that of heating the solutions of the surrounding rocks. In Chapter III, on "The agents of metamorphism," it has been explained that solutions gain marvelously in their metamorphic power by heat, and adjacent to igneous rocks the temperature may reach or even surpass that of the critical temperature of water. While by conduction high temperature progresses from the magma, by convection, where the circulation is vigorous, solutions having a high temperature are carried over wide areas. In this treatise contact metamorphism is considered in three places, for the nature of the contact action, like that of other forms of metamorphism, is very different in the different belts and zones. Therefore the subject of contact metamorphism is considered under the belt of weathering, the belt of cementation, and the zone of anamorphism. In this chapter only the first part of the subject is considered; the other parts may be found under the heading "Injection," on pages 646–652.

In the belt of weathering contact metamorphism comprises (1) the direct contact effect and (2) the indirect effect through gaseous solutions. This second is ordinarily called the action of fumaroles and solfataras.

DIRECT CONTACT EFFECT.

The direct contact effect is produced by conduction of the heat of the magma into the surrounding rocks. The temperature of the rocks immediately adjacent to the igneous rocks may become very high—indeed, approach that of fusion, and possibly reach a fusion temperature locally. Under these circumstances the complex mixtures of minerals characteristic of the belt of weathering, including the hydrates, silicates, and other forms, are likely to be baked, and thus indurated. The hydrous minerals may be dehydrated, and thus to this extent the ordinary reactions of the belt of weathering are reversed. The zeolites, serpentines, talcs, chlorites, etc., where dehydrated, are destroyed. Limonite may be changed to hematite, gypsum to anhydrite, etc. From the carbonates the carbon dioxide may be driven off or calcination take place, and thus lime and magnesia be produced. This gives the rocks an alkaline reaction, so that contact action on such rocks in the belt of weathering is sometimes called "caustic" action.

The general contact effects of dry heat have been called, depending upon the degree of action, baking, fritting, and vitrification. Irving gives the following illustrations of these processes:

Sandstones are decolorized and often fritted to a glistening enamel-like or porcelanic mass; in other cases, where the cement is of a calcareo-argillaceous nature, this is melted into a glass; clay and mud are converted into porcelanite or brick, with marked change of color in many cases; tuffs and phonolites are so far vitrified as to acquire a character resembling that of obsidian; brown coal is altered into seam coal or anthracite, and these in other cases into a substance more resembling graphite, while in others (probably under less pressure) the coal is converted into coke, the various shades of metatropic change of brown coal into anthracite, carbon-glance, bituminous coal, and black coal being observed in some cases in the same section through several meters of the mass; a prismatic structure is developed, not only in clays and marls, but even in sandstones, in brown coal, in seam coal, and in dolomite; limestones are altered into crystalline marble, often with complete effacement of their stratification and even of all traces of their fossils; the finer varieties of grauwacke and its associated shales are converted into hornstone, as in the classical region of the Brocken.

Of these metatropic changes by the action of dry heat under pressure that of the formation of marble has been experimentally verified years ago by G. Rose and more recently by Richthofen and others.[a]

Usually all of the direct dry heat contact effects are very limited in amount, extending only short distances from the igneous rocks. Ordinarily the direct effect is modified by indirect effects. In many of the cases mentioned by Irving, where the material when modified was not in the belt of weathering, it is highly probable that the results were not accomplished by dry heat alone, but with the assistance of gases and vapors. Commonly the rocks which are being baked, fritted, or fused are in the midst of gases and vapors, including, of course, abundant water vapor and oxygen. Also, as in the cases mentioned by Irving, in many instances which have been given of the effect of dry heat alone the material when altered was below the belt of weathering; but as the different cases of metamorphism attributed to dry heat have not been studied in reference to the different zones and belts of metamorphism, and it is therefore impossible to discriminate with certainty the cases which are truly due to dry heat alone from those in which heat works in conjunction with gases and vapors, or even in conjunction with water, in so far as the gases and vapors are present, we have the indirect effects considered below mingled with the direct contact effects.

INDIRECT CONTACT EFFECT, OR WORK OF FUMAROLES AND SOLFATARAS.

It has been said that the indirect contact action is due to gaseous solutions. The action of such solutions may extend much farther than the direct contact effect. The belt of weathering may be permeated locally with hot gaseous solutions. The work of these gaseous solutions is essentially of the same nature as that of ordinary gaseous solutions, discussed on the previous pages (see pp. 59–63); but the gaseous solutions adjacent to igneous rocks usually contain a greater quantity of the active chemical agents than do ordinary solutions; and, moreover, their temperature is much higher than normal. This gives a combination of conditions which results in much more rapid alteration than the average of the belt of weathering and alteration of a different kind. The exceptional regions in which these unusual conditions obtain are volcanic. In volcanic regions

[a] Irving, A., Chemical and physical studies in the metamorphism of rocks, Longmans, Green & Co., London, 1889, p. 76.

the so-called fumarolic and solfataric[a] actions may occur on an extensive scale. In such regions fumarole is generally applied to the gases at the higher temperatures, and solfatara to the gases at moderate temperatures, although this distinction is not everywhere applied. Fumarolic and solfataric action is therefore largely the work of gaseous solutions, although liquid solutions are also at work to an important extent. The gases may be widely dispersed through the porous rocks, but in many cases they move chiefly along large definite channels, from which they spread for various distances along smaller and less definite openings.

Of the gases of fumaroles and solfataras, water vapor is dominant. In many districts it is emitted in enormous quantities from the orifices. Probably the gas next in abundance to steam is sulphurous oxide (SO_2). Other important gases are chlorine (Cl_2), hydrochloric acid (HCl), hydrofluoric acid (HFl), hydrosulphuric acid (H_2S), sulphuric acid (H_2SO_4), carbon dioxide (CO_2), oxygen (O_2), and hydrogen (H_2). Boric acid (H_3BO_3), is sometimes plentiful; nitrogen (N_2), is abundant; and hydrocarbons occur. The proportions of these gases are very different in different localities. In many cases the differences seem to be a function of the temperatures of the fumaroles and solfataras. In the very hot fumaroles chlorine, hydrochloric acid, and hydrofluoric acid are likely to be abundant. At lower temperatures sulphurous oxide and hydrosulphuric acid are very common, and at still lower temperatures oxygen, carbon dioxide, and nitrogen are abundant. In the hot fumaroles, associated with the strong acids characteristic of them, are also found many of the compounds characteristic of fumaroles and solfataras of lower temperatures, although these may be overlooked. With all classes of fumaroles and solfataras water vapor is dominant, but it is frequently more markedly dominant at the lower than at the higher temperatures.

The source of the gases of fumaroles and solfataras is a complex question of which I shall not attempt to give an adequate discussion. It is to be presumed, as pointed out on pages 931–937, that the ultimate source of the various products formed in the belt of weathering is the material of the original magmas. However, later it will be more fully explained that several of the rarer elements of the igneous rocks are locally concentrated in the belt of weathering by various processes. To what extent the active gases of the volcanoes are derived from the original magmas and what part from the later concentrations of these I shall not here consider.

---

[a] Latin *fumus*, smoke, and Italian *solfo*, sulphur.

The source of the most abundant vapor emitted during volcanic action has been much discussed. Some have held that the water is derived from the original magmas, never having been at the surface, while others have held that it is derived from the water of the surface and underground circulation. It may be in part derived from each. Chlorine, hydrochloric acid, hydrofluoric acid, and hydrosulphuric acid are undoubtedly largely formed by the action of hot water upon chlorides, fluorides, and sulphides. Sulphurous and sulphuric oxides are produced by the action of the oxygen upon the sulphides. These may unite with water and produce sulphurous and sulphuric acid. To what extent the above chlorine, fluorine, and sulphur compounds are derived directly from the magmas and to what extent from later segregations containing an unusual amount of these elements it is not my purpose here to discuss. The hydrogen of fumaroles and volcanoes is usually regarded as due to the decomposition of water.[a] This may be accomplished by ferrous oxide according to the following equation:

$$H_2O+2FeO=H_2+Fe_2O_3.$$

The immediate source of a part of the hydrogen is probably hydrosulphuric acid, the hydrogen being liberated as this acid decomposes and the sulphur separates. But since the H_2S is probably produced, as already explained, by the action of H_2O on sulphides the hydrogen is indirectly derived from the water. It is shown that carbon dioxide is extensively liberated by the process of silication in the zone of anamorphism. (See pp. 677–679.) It is natural to suspect that this liberated carbon dioxide largely makes its way to the surface at places where there is active upward circulation. Volcanic districts are certainly such places. Hence it is believed that much of the carbon dioxide issuing in connection with fumaroles and solfataras is that liberated by silication. Where carbonates are present as rocks adjacent to volcanoes another portion of the carbon dioxide is doubtless derived by the action of the strong acids upon these carbonates, salts of the strong acids being produced and the carbon dioxide liberated. No opinion is expressed as to the relative abundance of these two sources of carbon dioxide.

As would be expected, the ordinary reactions of the belt of weathering take place in regions of fumarolic and solfataric action the same as else-

[a] Geikie, Sir Archibald, Text-book of Geology, Macmillan & Co., London, 1893, 3d edition, pp. 193–197.

where. Indeed, these reactions probably take place at a greatly accelerated rate. Therefore in areas of fumarolic and solfataric action oxidation, carbonation, hydration, and solution are important reactions, but ordinarily this is not recognized because of the more striking action of the exceptional compounds which are present in unusual abundance. That oxidation takes place on an extensive scale is shown by the yellow, red, or brown colors of the altered rocks due to limonite, hematite, and magnetite which extensively form from the monoxide of iron. Hydration in connection with fumaroles and solfataras has been to a considerable extent overlooked. Delesse found that dry steam at a pressure of five atmospheres had no appreciable action upon minerals. Barus found that the diabase of the Comstock lode, containing fresh feldspar, was not kaolinized by the long-continued action of steam at 100° C.[a] However, it is rare that steam is dry in the actual case of fumaroles and solfataras, and therefore, as would be expected at high temperatures, the process of hydration goes on at a great rate. Carbonation also takes place on a scale scarcely less extensive than hydration. In consequence the formation of sodium carbonates is very common and in some places it is found in large quantities.

However, it is not by these common products but by the exceptional products that fumarolic and solfataric action is especially distinguished. The chlorine and hydrochloric acids form chlorides, of which sodium chloride ($NaCl$), potassium chloride (KCl), ammonium chloride (NH_4Cl), iron chloride ($FeCl_3$), copper chloride ($CuCl_2$), manganese chloride ($MnCl_2$), and other chlorides have been observed. Through the action of sulphuric acid various alums are formed, of which potassium-aluminum sulphate and sodium-aluminum sulphate are the more common. By action upon calcium-bearing compounds sulphuric acid forms gypsum. By action upon the alkali-bearing compounds the sulphuric acid forms Glauber's salt, or sodium sulphate, and potassium sulphate. The action of hydrosulphuric acid upon the various compounds may form various sulphides, or it may be decomposed without action upon other substances, in which case it liberates hydrogen and deposits sulphur. The hydrofluoric acid attacks the various compounds, forming various fluorides, of which fluorite is the best known. The boric acid forms borates. Of these various sub-

[a] Barus, C., On the thermal effect of the action of aqueous vapor on feldspathic rocks: School of Mines Quart., vol. 6, 1884, pp. 1–23.

stances formed, some are volatile and may be sublimed. Among these ammonium sulphate, sulphur, and boric acid are well known.

While any of the minerals present may be acted upon, on the average the silicates are decomposed on a far greater scale than other compounds; for silicates are the dominant salts present which the active agents find to work upon. Besides producing the various compounds above mentioned, which are especially characteristic of fumarolic and solfataric action, the relatively insoluble residual products of the silicates are extensively produced, such as kaolin, etc. While these chemical reactions are taking place, concurrently with and depending upon them the rocks are softening, and the result is to produce a whitish or yellowish earth, frequently stained red where iron oxide is abundant. So long as the fumarolic and solfataric action continues, mingled with this residual material are many of the soluble compounds mentioned above; but after fumarolic and solfataric processes cease, the soluble salts are rapidly leached out by the ground water circulation and there remains the residual, relatively insoluble compounds characteristic of the belt of weathering.

In summary it may be said that fumarolic and solfataric action is not so different from the ordinary reactions of the belt of weathering as might be supposed. The reactions are essentially the same. All of the reactions characteristic of the belt of weathering occur, but at a more rapid rate than ordinarily. Moreover, the local concentration of numerous strong acids makes their action of relatively greater importance than under the ordinary conditions of the belt of weathering. Finally, in the case of fumaroles and solfataras the process of decomposition is wholly chemical, whereas ordinarily in the belt of weathering organic compounds play an important part.

In a strict sense fumarolic and solfataric action, so far as it is the action of gases, is that of mineralizers, as defined by Naumann. However, fumarolic and solfataric action as here considered is not that which is ordinarily known as the action of mineralizers; hence I have avoided the term.

RELATIONS OF DISINTEGRATION TO DECOMPOSITION AND SOLUTION.

The mechanical work of weathering is the physical subdivision of the material; in other words, is disintegration. The chemical work of weathering is decomposition and solution. The process of disintegration promotes the chemical work of decomposition and solution, because, as disintegration

goes on, the surfaces exposed to the action of the chemical agents become larger. If a mass of material, of whatever size, be divided into any number of parts with similar forms, the total area of the new surfaces will be equal to that of the original surfaces multiplied by the square root of the number of parts. For instance, if a given mass of rock be divided into a hundred parts, with forms similar to the original mass, the surface is increased ten times, and therefore the area subjected to chemical action is increased tenfold. Hence, in so far as the rocks are broken mechanically, they give greater surface of action, and this surface of action increases directly as the comminution increases. It follows that the finely comminuted material is much more readily decomposed than the coarser material. Loughridge has shown that the amount of soluble material in soils is, on the average, larger in proportion to the comminution, thus confirming the conclusion that increase in the surface is favorable to chemical action.[a]

But decomposition reacts upon disintegration. In proportion as the material becomes decomposed it is more readily broken up. In so far as the material is chemically altered, and especially in proportion as it is dissolved, the rock is weakened and thus the forces of disintegration rendered more effective. The mechanical and chemical forces therefore act and react upon each other, each one increasing the effectiveness of the other; hence disintegration greatly accelerates decomposition and solution, and decomposition and solution accelerate disintegration.

This action and reaction between the mechanical and chemical work is well illustrated by the experiments of Daubrée,[b] who found that various minerals and glass when mechanically triturated in a rotating cylinder are very readily acted upon by pure water, carbonated water, and water containing sodium chloride. In this way he produced a very fine, impalpable mud, which when dried resembled argillite and contained a high percentage of alkalies. It is clear from the above that the greatest effects in the way of weathering are produced by combination of the mechanical and chemical processes. Where, by the action and reaction of the mechanical and chemical agents, the subdivision has gone to such a stage that the particles are

[a] Loughridge, R. H., On the distribution of soil ingredients among the sediments obtained in silt analysis: Am. Jour. Sci., vol. 7, 1874, p. 17. Merrill, George P., Rocks, rock-weathering, and soils, Macmillan Co., New York, 1897, pp. 365–366.

[b] Daubrée, A., Géologie Expérimentale, Paris, 1879, pt. 1, pp. 268–279. Also, Merrill, George P., Rocks, rock weathering, and soils, Macmillan Co., New York, 1897, p. 197.

exceedingly minute, the surface exposed to action is enormous. As illustrating this, Whitney has calculated that there are 22 billion grains of sand and clay in a gram of residual subsoil from a limestone, and that the surface of these particles has an area of 5,000 square centimeters. This is an extreme case, but Whitney estimates the number of grains in ordinary soils to vary from 2 billions to 15 billions per gram.[a]

In an early stage of the process of subdivision disintegration usually plays the dominant part. As the material becomes finer chemical action becomes more important. When the particles become minute, chemical action is dominant in producing subdivision. As shown on pages 432–434, it may well be doubted whether the exceedingly minute subdivision of the residual clays from limestones could be accomplished by the mechanical agents of weathering alone.

It has been seen that the mechanical work of weathering is accomplished by wind, water, ice, change from water to ice, change in temperaature, plants, and animals. The chemical work is accomplished by plants, animals, and solutions. The various factors in this mechanical and chemical work interlock in a most complex fashion. An increase in the amount of work of one of the factors may increase or decrease the amount of work of another factor. Moreover, the kind of work accomplished by one factor is so different from that of another factor that it is difficult or impossible to make quantitative comparisons between them. Thus it is impossible to compare the mechanical work of disintegration with the chemical work of decomposition.

The particular combination of agents and forces most actively at work at a given place is largely dependent upon humidity, latitude, elevation, and life. There are very numerous permutations and combinations of these, so that the number of variations in the rate of weathering are indefinitely great.

REGIONS FAVORABLE TO PROMINENCE OF DISINTEGRATION.

The regions favorable to prominence of disintegration are those of (a) aridity, (b) high latitude, (c) marked topographic relief, (d) sparseness of plants and animals, and (e) nearness to the sea.

Arid regions.—It has already been seen (pp. 438–439) that in arid regions the mechanical stresses due to rapid change in temperature and to the wind

[a] Whitney, Milton, The soils of Maryland: Bull. Maryland Agr. Exp. Sta. No. 21, 1893, pp. 8, 33–57.

are potent influences in breaking up the rocks. By insolation the rocks may be coarsely subdivided; by the wind, bearing sand, they may be finely subdivided—both with very little chemical action. In many dry regions the rainfall is largely concentrated into a small part of the year. In some regions this rainfall may occur as severe local storms. Under these circumstances the disintegrated products are stripped from the rocks by the running water, thus exposing new surfaces to weathering. The transported material may be carried to the sea or may be accumulated in the lower levels between the steep slopes. The former case is illustrated by the sedimentary rocks which are now forming in the Gulf of California. McGee describes the granitic and other rocks of southern California as being simply split apart and broken into their individual grains, which are transported at rare times of abundant rainfall by the process which he calls sheet-flood erosion and deposited in the Gulf of California with scarcely any chemical change Such rocks may have very nearly the average chemical composition of the original rocks from which they are derived.[a]

Very frequently the disintegrated material of arid regions does not reach the sea, but accumulates in the lower areas. Hilgard notes that the soils of such regions are "predominantly sandy or silty, with but a small proportion of clay, unless derived directly or indirectly from preexisting formations of clay or clay shales."[b] Moreover, he notes that the soil and the subsoil are substantially the same. The deficiency of clay—that is, kaolin—is explained by the lack of the decomposition of the feldspars. The deficiency of clay is no less marked in these soils than the abundance of alkalies and alkaline earths. Hilgard finds the proportions of these elements in arid and humid regions to be as follows:[c]

	Arid region (per cent).	Humid region (per cent).
Potash	0.825	0.187
Soda	.251	.071
Lime	1.645	.112
Magnesia	1.384	.209

[a] McGee, W J, The formation of arkose: Science, new ser., vol. 4, 1896, pp. 962–963.

[b] Hilgard, E. W., Relations of soil to climate: Bull. Weather Bureau No. 3, U. S. Dept. Agric., 1892, p. 17.

[c] Hilgard, cit., p. 30.

The soils of the arid regions investigated by Hilgard therefore contain from four to fourteen times more of the elements potassium, sodium, calcium, and magnesium, than do those of the humid regions. This difference is doubtless due in part to lack of decomposition of the original compounds; but it is also due in part to the fact that the decomposed materials of the arid regions have not been leached as they have been in the humid regions. As shown in another place (pp. 541–543), the soluble constituents resulting from the decomposition of the original minerals are largely retained.

In conclusion, we see that aridity or low humidity is generally favorable to mechanical rather than to chemical work. In arid regions the process of disintegration is rapid, and that of decomposition and solution is slow. The total rate of weathering in arid regions, including mechanical and chemical work, is probably, on the average, less rapid than in humid regions.

Regions of high latitude.—First, regions of high latitude are those of low temperature. It has already been seen that the disrupting effect of change from water to ice is an important factor in the disintegration of rocks. This process is applicable only to those regions in which the temperature falls below 0° C., and to such regions for only those parts of the year in which the temperature alternately passes above and below the zero mark. These conditions at low altitude do not occur at all in the Tropics. They occur in winter only in the parts of the temperate zones near the Tropics. They occur in spring and autumn in the cooler parts of the temperate zones and in the frigid zones. However, in passing from low to high latitude the length of time during each year in which the conditions are those of alternate freezing and thawing increases; also the range above and below zero increases. Hence the disintegration due to freezing and thawing increases as the latitude increases from those parts of the temperate zones near the Tropics to the far northern and southern lands. Second, regions of high latitude are those of extensive glaciation. The glaciers are most powerful disintegrating agents, producing débris ranging in size from great bowlders to the minute particles which whiten the waters issuing from them, and all this with scarcely a trace of decomposition. Third, in regions of high latitude there are great changes in temperature which work by differential expansion, as explained on pages 438–439, and thus help to disintegrate the rocks. Absence of decomposition in connection with disin-

tegration at high latitudes also follows from the low temperature, because very unfavorable to chemical action and to abundant organisms.

Therefore in regions of high latitude the rocks are ordinarily broken down and not greatly changed chemically. The exceedingly rapid and extended disintegration of the rocks in regions of high latitude is well illustrated by such countries as Greenland, Spitzbergen, Franz Josefs Land, etc. As in the arid regions, the sedimentary rocks formed in regions of high latitude may be composed of disintegrated materials, chemically essentially like the materials from which the rocks are derived. As in the arid regions, where mechanical materials from different sources are mingled, they represent the average composition of the original rocks rather than any one original rock.

Regions of marked topographic relief.—Regions of marked topographic relief are usually regions of considerable elevation. In such regions the mechanical forces work under most favorable conditions. Gravity pulls the material down the steep slopes. The range in temperature is great; water alternately freezes and thaws; glaciers are prevalent. Consequently material is split or ground from the solid rocks and is carried by gravity in great quantity to lower levels.

The remarkable effect of elevation and sharp relief in disintegration is especially well illustrated in high mountain ranges. In such regions great and small masses are split from the cliffs by the disintegrating forces and agents or are carved from the valley floors by the glaciers, and are transported to a lower level by water or by ice with scarcely appreciable chemical change The cirques at the heads of glaciers give excellent illustrations of the very great rapidity of disintegration due to the combination of the above causes. The Matterhorn, with its sharp triangular peak and the great cirques at its base, is a most impressive illustration of such disintegration. The peaks of the High Sierras and the Canadian Rockies afford many fine illustrations of the same process.

Penck suggests that the average altitude of mountains in any given region for a given kind of material is limited by the fact that disintegration increases so rapidly as the height increases that for any given area there is a height where the forces of disintegration degrade the mountains as fast as the forces below are able to lift them.[a]

---

[a] Penck, A., Morphologie der Erdoberfläche, J. Engelhorn, Stuttgart, 1894, pt. 2, pp. 334–335.

Also the low temperature is unfavorable to chemical action and to life, and transportation follows closely upon disintegration. The result, therefore, of marked topographic relief is rapid disintegration with comparatively little decomposition.

Regions of sparse plants and animals.—That sparseness of plants and animals is favorable to disintegration without decomposition has already been shown, since it has been made clear that decomposition is largely dependent upon the action of plants and animals and their by-products. The sparseness of life may be due to low temperature, low humidity, or other causes.

Regions near the sea.—Nearness to the sea or to a large river is favorable to disintegration with subordinate decomposition, since the material is transported only a short distance before it is deposited below the water. But this relation is not so important as one might at first think. The amount of decomposition is far more dependent upon whether the conditions are favorable for this process before the material reaches the large streams than upon distance from the sea.

When the material once gets permanently below the surface of the water, it passes to a considerable extent from the conditions of the belt of weathering to those of cementation. While oxygen and living organisms may still act upon the material, they are not nearly so effective as under the conditions of the belt of weathering; hence, the process of decomposition is much retarded. This is well illustrated by the material brought down by the Nile and deposited in its lower reaches. According to Judd, the deposits of the Nile delta consist of fresh, unaltered, rounded, angular and subangular grains of the original minerals of the rock, such as the feldspars, hornblende, augite, quartz, etc. This material, he says, has been derived from the desert sands, which lie on either side of the Nile Valley and are swept into it by the wind.[a] As has been seen (pp. 496–498), desert conditions are favorable to disintegration without decomposition; hence the sands contributed to the upper Nile are little decomposed, and the long river journey does not greatly increase the amount of decomposition.

While decomposition largely ceases when the material is transported by streams, disintegration does not cease, for the particles grind against one another or over the bottom, and thus comminution goes on; and therefore the

[a] Judd, J. W., Report on a series of specimens of the deposits of the Nile delta, obtained by the recent boring operations: Proc. Royal Soc. London, vol. 39, 1885, pp. 213–220.

longer the journey the farther this process continues. However, as shown on pages 432–434, there appears to be an inferior limit in size, beyond which attrition ceases; that is, the particles become so fine that they are floated and have not sufficient weight and momentum to materially grind one another. This conclusion is further supported by the fact, given by Judd, that the small particles of the alluvial deposits of the Nile which have been transported great distances are angular, while the larger particles of the same deposits are subangular or rounded. However, he attributes the rounding of the larger grains to eolian rather than river erosion; but this does not lessen the force of the argument as to there being a lower limit beyond which the particles are not rounded by river action. Further evidence in the same direction is the angular character of the loess of the Mississippi Valley. Chamberlin and Salisbury found that the loess of that valley, much of which must have been floated for long distances, probably hundreds of miles, is wholly composed of angular particles which show no evidence of wear. For the most part these loess grains are less than 0.005 mm. in diameter, although in some places 1 per cent or more exceed this diameter, and a few grains are nearly 0.1 mm. in diameter.

REGIONS FAVORABLE TO PROMINENCE OF DECOMPOSITION.

The regions favorable to decomposition are those of humidity, low latitude, moderate topographic relief, abundance of plants and animals, and remoteness from the sea.

Humid regions.—It is clear that humidity is one of the requisite conditions for regions of rapid decomposition, since chemical action is very slow in the absence of water. In humid regions, as already shown, the belt of weathering always contains a large and variable amount of water, and water is essential for vigorous chemical action. Hydration is one of the chief reactions of the belt of weathering, and in humid regions there is abundance of the necessary compound for the process.

High humidity may occur at any latitude and at any elevation. At low latitudes and low elevations the temperature is high and life is abundant, and these conditions are especially favorable to chemical work.

As evidence of decomposition in the humid regions, Hilgard contrasts the soils of such regions with those of the arid regions, and finds that in the humid regions the soils are usually loams with a clay subsoil. The presence

of clays, of which kaolin is the chief constituent, proves the extensive decomposition of the silicates, especially the feldspars.

It is rather probable that decomposition is most rapid in regions of moderate humidity, where there is moisture sufficient to carry on decomposition, solution, and transportation of the disintegrated material with considerable rapidity, and for animals and plants to be reasonably abundant, but not sufficient to produce extraordinarily luxuriant vegetation, which may practically stop mechanical transportation on all but the steepest slopes, and thus produce a protective covering of decomposed materials. (See p. 503.)

While humidity is very favorable to decomposition, it must be remembered that running water is the greatest of the eroding agents, and therefore that humidity is also very favorable to disintegration.

Regions of low latitude.—Regions of low latitude are those of high temperature. Warmth is favorable to chemical decomposition. The great increase in the activity of chemical agents in consequence of increase in temperature has already been explained on pages 61–62, 78–81, and hence in warm regions the chemical agents which are at work in the belt of weathering have a potency which they do not approach in cold regions. Therefore the usual deep belt of decomposition in the tropical and semitropical regions and the general absence of such a belt in the colder regions is partly explained by high temperature.

Consequent upon high temperature as one essential factor is abundant life, which still further favors decomposition, as explained below. In regions of high temperature the range of temperature may be great, and therefore disintegration due to this cause be a concurrent process. But in such regions the temperature does not often fall below zero, and hence the disintegrating effect of freezing and thawing is nil, or nearly so.

Regions of moderate topographic relief.—Regions of small topographic relief generally have gentle slopes, and gentle slopes are favorable to retention of moisture and unfavorable to rapid transportation. Moreover, regions of small relief usually have low elevations and are favorable to high temperature, and consequently to abundant life. Hence, regions of small elevation are those of marked decomposition.

If the elevation be slight the level of ground water may be at a very small depth below the surface, or even reach the surface, and thus decom-

position be stayed. But areas of very low relief are favorable to decomposition of the narrow belt extending to and somewhat below the level of ground water. This is well illustrated by Florida. In that region the original refractory minerals have been decomposed and the soluble material abstracted; and the relatively soluble minerals, such as the calcium carbonate of the limestones, have been wholly abstracted, leaving for a large part of the region a mantle of insoluble residual material, corresponding in composition almost perfectly with the ultimate products of weathering. (See pp. 520–521.)

In contrast with low regions are regions where the altitudes are great and the slopes steep. Disintegration and transportation may go on so rapidly as to give little opportunity for decomposition.

Thus the most favorable conditions for most rapid but not complete decomposition are limited both by very low and by very high altitudes. Therefore, the most favorable topographic conditions for rapid decomposition are those of moderate relief. Excellent illustrative regions are southeastern United States, Nicaragua, and large parts of Brazil. These are all regions of moderate elevation and continuous moderate slopes.

Regions of abundant plants and animals.—Plentiful plant and animal life is very favorable to decomposition. Abundance of plants and animals is conditioned by high humidity and high temperature. Regions of abundant life are therefore the warm, moist regions of the Tropics and the sub-Tropics. It is not too much to say that abundant animals and plants and their by-products are the sources of most of the active compounds, which, working through abundant water solutions favored by high temperature, do the great work in the decomposition of the rocks. As already pointed out, the process of carbonation, one of the chief reactions of the belt of weathering, is largely conditioned on the carbonic acid concentrated by the decomposition of plants and animals.

While the work of life is fundamental in the decomposition of the rocks, where life is too abundant this may stay the progress of weathering. Abundant plant life gives a protective covering to the decomposed rocks, which is effective in proportion to its luxuriance. The plant covering, where very luxuriant, as in many parts of the warm regions, very greatly retards, and may almost wholly stop, the mechanical work of disintegration and transportation. Therefore, under these conditions, in very humid

regions decomposition frequently outruns transportation, and a thick layer of decomposed material accumulates. Finally, there may be produced a thick, nearly permanent, belt of weathered material which is protected from mechanical transportation by vegetation and protects the rocks below from decomposition. Such appear to be the conditions in Nicaragua along portions of the proposed route of the ship canal. Hayes says that in parts of Nicaragua, notwithstanding the complete decomposition of the rocks and the abundant rains, the streams are clear.[a] The process of weathering must therefore be very slow, being almost wholly limited to solution.

Regions remote from the sea.—In so far as the material is remote from the sea it is long exposed to the forces of weathering before it is finally floated or deposited in the sedimentary rocks, and thus in proportion as the material is transported far before permanently reaching the water it is likely to be decomposed.

General statements.—While in the previous pages an attempt has been made to consider separately humid regions, regions of low latitude, regions of moderate topographic relief, regions of abundant plants and animals, and regions remote from the sea, in speaking of one it has been necessary to some extent to consider one or more of the others. In regions which combine several of these factors decomposition is at a maximum. It is only when the materials of the belt of weathering in regions of high latitude, high altitude, and aridity, in which life is sparse, are compared with the materials of the belt of weathering in humid regions, regions of low latitude, low altitude, and abundant life, that the efficiency of the latter combination of conditions in the decomposition of rocks can be fully appreciated. It has been seen that where the former set of conditions obtain, weathering consists in rapid change of temperature, change of water to ice, and the work of glaciers splitting or grinding the rocks into fragments; but that the particles in chemical and mineral composition are substantially the same as the original rock, although, of course, decomposition does always take place to some extent. But in warm humid regions, in which plant life and animal life are abundant, the solid rocks are not only disintegrated, but the material is rapidly decomposed. This decomposition may extend from a few meters to a depth of 90 meters in the subtropical and tropical regions. A result of high humidity and high temperature are the wonderfully luxuriant

[a] Hayes, C. W., Report of the Nicaragua Canal Commission, Appendix II, Geologic Report, Baltimore, 1899, p. 112.

forests of the Tropics, such as those of Brazil and central Africa. The difficulties of traversing such a region are almost incredible. The forests are a tangle of vegetation, which it is possible to penetrate only by cutting one's way. Under such conditions the rocks in the belt of weathering are continuously acted upon in the most powerful way, under the most favorable conditions of humidity and temperature, by the chemical products furnished by the plants and animals, alive and dead. No one can realize the abundance of plant and animal material, dead and alive, both above and below the soil, in a dense forest region without traveling through one. The soil for many feet below the surface seems to be mainly composed of vegetation. The individuals vary from great trees, through plants of medium size, to the smaller plants, such as the mosses, fungi, and finally the bacteria. To a large extent the living plants are feeding on the dead and decomposing ones. At the surface the quantity of organic material is at a maximum. Normally the quantity steadily decreases from the surface to a depth of 12 to 15 meters, where it becomes unimportant. Thus there is every gradation between places at the surface where the organic material occupies the larger part of the space to a place below the surface where the inorganic material occupies all the space.

One who has studied regions where life is dense will readily believe that great geological consequences follow from the chemical activity of compounds produced by animals and plants, both alive and dead. It is not too much to say that life is an essential factor in far the larger part of the chemical work of decomposition and solution of the rocks.

Of the plants. the minute bacteria are among the most important. Of the animals, earthworms are perhaps the most important. The prodigious numbers of these compensate for their smallness. They furnish a striking illustration of the principle that small numerous agents may be more potent than large and more conspicuous but less numerous ones.

From the foregoing it is plain that living and dead plants and animals interact with one another and with the rocks in the production and maintenance of the soil. As shown on pages 452–453, chlorophyll-bearing plants, and especially one group of them, the leguminosæ, working in conjunction with bacteria, are the agents which collect carbon and nitrogen from the atmosphere and place them in the soil in a combined state. Dead plants and animals are the materials upon which living bacteria, oxygen, and water work to produce carbonic, nitric, and sulphuric acids. These form carbon-

ates, nitrates, and sulphates in great abundance within the soil, and thus the processes of carbonation, nitration, and sulphation of the minerals of the rocks are rapid. The carbonates, nitrates, and sulphates furnish food for the chlorophyll-bearing plants. The plants are food for the animals. After a time these plants and animals die, decompose, and thus supply additional material to carry on the process of decomposition of the rocks. Therefore there is action and interaction between the chlorophyll-bearing plants and the bacteria, and between these and the animals alive; interaction between these plants and animals dead and bacterial plants alive, and interaction between all live and dead plants and animals and the rocks. Decomposition of rocks produces plant food; the food builds the plants: the plants build the animals; these in turn, both while alive and after death, produce decomposition of the rocks, and so round indefinitely.

It is now clear why it is so difficult to produce a good soil where such a soil does not exist, and why a soil once formed may be retained indefinitely by proper tillage. Where the soil is good and vegetation is abundant, the complicated machine is in full motion and is able to produce new soil as fast as the old soil is transported elsewhere by wind or water.

The cycles above considered do not include the whole case. The full geological cycle does not occur in the belt of weathering alone. As fully explained elsewhere (pp. 538–539, 612 et seq.), a portion of the salts dissolved during the decomposition of the rocks in the belt of weathering is transported to the belt of cementation and there precipitated; another portion goes to the sea. It is only when these portions are followed that a full comprehension of the complicated and far-reaching geological effect of weathering through plants and animals may be obtained. Here it will only be remarked that of the salts of the sea, calcium carbonate is produced by carbonation of the silicates, but this process is mainly dependent upon the plants. Thus the work of the plants furnishes the material for the hard parts of sea animals; these hard parts are the source of the great limestone formations; as a result of geological revolutions limestone formations built below the sea are raised and become land areas; upon these limestones soils of unusual fertility are formed, and this results in luxuriant plant and animal life, thus completing a cycle, one among the many geological cycles connected with plants and animals.

While life is especially potent in chemical work, the power of life in mechanical work is considerable.

CHANGE IN CHEMICAL COMPOSITION OF THE ROCKS.

So far as the change in the average chemical composition of rocks in the belt of weathering is concerned, solution is largely the final determinative factor; although, as has been seen, the amount and nature of the material dissolved are dependent upon all the many factors heretofore considered. By comparing the original chemical composition of rocks with the chemical composition of the partly disintegrated and decomposed equivalent rocks, one is able to obtain an approximate idea of the relative losses of the elements. In order to compare the losses which the various elements have undergone as a result of solution and transportation, it is necessary to suppose that some one element is insoluble and is not abstracted at all. Usually iron and aluminum have been chosen as the insoluble constituents. With these as a standard in most cases, but in some cases other elements, Merrill made the following calculations as to the losses of the elements for various rocks:[a]

Supposing the amount of iron to remain constant, for a disintegrated and partly decomposed granite in the District of Columbia the original composition and the losses of the constituents are as follows:

TABLE I.—*Analyses of fresh and altered granite.*

Constituent.	Original composition.	Loss for each constituent.
	Per cent.	*Per cent.*
Silica	69.33	14.89
Alumina	14.33	3.23
Ferric oxide / Ferrous oxide	3.60	0.00
Lime	3.21	25.21
Magnesia	2.44	1.49
Soda	2.70	28.62
Potash	2.67	31.98
Phosphoric anhydride	0.10	40.00
Ignition	1.22	0.00
Total	99.60	.....

[a] Merrill, George P., Rocks, rock-weathering, and soils, Macmillan Co., New York, 1897, pp. 209–232.

Supposing the amount of aluminum to be constant (except in Table III, analysis 2, fresh diabase from Venezuela, in which iron is supposed to be constant), the original composition and the losses of the various elements for the following rocks are as follows:

TABLE II.—*Analyses of fresh and altered gneiss and syenite.*

Constituents.	Fresh gneiss (Virginia).	Fresh syenite (Arkansas).
	Original composition.	
	Per cent.	*Per cent.*
Silica	60.69	59.70
Alumina	16.89	18.85
Ferric oxide	9.06	4.85
Lime	4.44	1.34
Magnesia	1.06	.68
Potash	4.25	5.97
Soda	2.82	6.29
Phosphoric acid	.25	.....
Ignition	.62	1.88
Total	100.08	99.56

Constituents.	Decomposed gneiss.	Decomposed syenite.
	Loss for each constituent.	
	Per cent.	*Per cent.*
Silica	52.45	62.18
Alumina	0.00	0.00
Ferric oxide	14.35	86.17
Lime	100.00	87.90
Magnesia	74.70	82.10
Potash	83.52	81.85
Soda	95.03	97.11
Phosphoric acid	0.00	.....
Ignition	0.00	.....

TABLE III.—*Analyses of fresh and altered diabase and basalt.*

	Fresh diabase (Massachusetts).	Fresh diabase (Venezuela).	Fresh basalt (Bohemia).	Fresh basalt (France).
	Original composition.			
	Per cent.	*Per cent.*	*Per cent.*	*Per cent.*
Silica	47.28	49.35	43.61	48.29
Alumina	20.22	15.30	12.26	13.25
Ferric oxide	3.66	----------	3.51	0.00
Ferrous oxide	8.89	12.28	12.16	16.66
Lime	7.09	9.60	11.37	7.33
Magnesia	3.17	7.38	9.14	7.03
Manganese oxide	.77	----------	----------	----------
Potash	2.16	.85	.81	1.81
Soda	3.94	1.98	2.72	2.71
Phosphoric acid	.68	----------	----------	----------
Ignition	2.73	3.25	H_2O 4.42	4.92
Total	100.59	100.00	100.00	100.00

	Disintegrated diabase.	Decomposed diabase.	Decomposed basalt.	Decomposed basalt.
	Loss for each constituent.			
	Per cent.	*Per cent,*	*Per cent.*	*Per cent.*
Silica	18.03	42.40	32.99	65.56
Alumina	0.00	21.38	0.00	0.00
Ferric oxide / Ferrous oxide	18.10	0.00	50.17	88.84
Lime	25.89	83.23	84.53	47.24
Magnesia	21.70	61.37	74.10	96.38
Manganese oxide	41.57	----------	----------	----------
Potash	29.15	45.88	61.69	83.34
Soda	12.83	95.37		74.41
Phosphoric acid	11.39	----------	----------	----------
Ignition	0.00	0.00	----------	0.00

TABLE IV.—*Analyses of fresh and altered diorite, pyroxenite, and argillite.*

	Fresh diorite (Virginia).	Pyroxenite (Virginia).	Fresh argillite (Maryland).
	Original composition.		
	Per cent.	*Per cent.*	*Per cent.*
Silica	46.75	38.85	44.15
Alumina	17.61	12.77	30.84
Ferric oxide	16.79	12.86	14.87
Lime	9.46	6.12	.48
Magnesia	5.12	22.58	.27
Potash	.55	.19	4.36
Soda	2.56	.11	.51
Phosphoric acid	.25	.....	.....
Ignition	.92	6.52	4.49
Total	100.01	100.00	99.97

	Decomposed diorite.	Decomposed pyroxenite.	Decomposed argillite.
	Loss for each constituent.		
	Per cent.	*Per cent.*	*Per cent.*
Silica	37.31	43.58	57.57
Alumina	0.00	0.00	0.00
Ferric oxide	21.03	41.48	8.78
Lime	97.30	44.45	100.00
Magnesia	97.17	76.19	28.16
Potash	38.75	47.05	77.95
Soda	84.87	0.00	99.64
Phosphoric acid	19.87	.....	.....
Ignition	0.00	20.26	.....

One of the best cases of complete decomposition known to me is that of the diabase of the iron-bearing formation of the Penokee-Gogebic district. In this rock in its most altered form not one vestige of any original mineral was discovered with the microscope. While the analyses of this rock are here inserted, it was largely altered below the level of ground water, but at a point where abundant descending waters from the belt of weathering were converged, and where therefore the conditions were intermediate between those of the belt of weathering and those of the belt of cementation. The

analyses of the fresh diabase and the decomposed rock are given in columns 1 and 2. Supposing the alumina to have remained constant, the losses of the other constituents are as given in column 3.

TABLE V.—*Analyses of fresh and altered diabase.*[a]

	1	2	3
H_2O at 105°	0.15	0.29	0.00
H_2O at red heat	2.34	13.54	
CO_2	.38	.38	58.06
SO_3[b]	.03	.....	.....
P_2O_5	.13	.14	54.83
SiO_2	47.90	41.60	63.57
TiO_2	.82	3.79	0.00
Al_2O_3	15.60	[c]37.20	0.00
Fe_2O_3	3.69	3.21	63.51
Cr_2O_3	Trace.	.....	100.00
FeO	8.41	.30	98.51
NiO(CoO)	.10	.....	100.00
MnO	.17	.08	80.26
BaO	.05	Trace.	99.00+
CaO	9.99	.23	99.04
MgO	8.11	.02	99.90
K_2O	.23	.....	100.00
Na_2O	2.05	.07	98.57
Total	100.15	100.85	.....

[a] Irving, R. D., and Van Hise, C. R., The Penokee iron-bearing series of Michigan and Wisconsin: Mon. U. S. Geol. Survey, vol. 19, 1892, p. 357.

[b] SO_3 calculated from BaO found, as this latter probably exists as $BaSO_4$.

[c] Al_2O_3 is probably a little high, owing to alkali retained by titanic acid.

Upon the supposition that no potash is lost in the case of a phonolite, the original composition and the losses are as follows:

TABLE VI.—*Analyses of fresh and altered phonolite.*

	Fresh phonolite (Bohemia).
	Original composition.
	Per cent.
Silica	55.67
Alumina	20.64
Ferric oxide	3.14
Lime	1.40
Magnesia	.42
Potash	5.56
Soda	7.12
Ignition	4.33
Total	98.28

	Decomposed phonolite.
	Loss for each constituent.
	Per cent.
Silica	8.54
Alumina	1.60
Ferric oxide	100.00
Lime	16.34
Magnesia	4.35
Potash	.00
Soda	65.99
Ignition	.00

Supposing the amount of silica remains constant in a limestone, the original composition and the losses are as follows:

TABLE VII.—*Analyses of fresh and altered limestone.*

	Fresh limestone (Arkansas).
	Original composition.
	Per cent.
Silica	4.13
Alumina	4.19
Ferric iron	2.35
Manganic oxide	4.33
Lime	44.79
Magnesia	.30
Potash	.35
Soda	.16
Water	2.26
Carbonic acid	34.10
Phosphoric acid	3.04
	100.00
	Residual clay.
	Loss for each constituent.
	Per cent.
Silica	0.00
Alumina	11.35
Ferric iron	89.56
Manganic oxide	57.59
Lime	98.93
Magnesia	89.38
Potash	66.37
Soda	53.26
Water	41.63
Carbonic acid	100.00
Phosphoric acid	89.76

While in the foregoing tables, with the exception of one rock spoken of as disintegrated, the altered forms of the rocks are classed as decomposed, it must be understood that these terms are relative. In the so-called

decomposed rocks the processes of decomposition have gone to different stages In but few of the rocks analyzed has the process nearly approached completion. Also the rock which is spoken of as disintegrated has been partially decomposed. This is conclusively shown by the fact that there is great variability in the calculated losses for the various elements. If the rock had simply been mechanically disintegrated the composition of the altered rock would have been the same as that of the original rock.

In the tables the various elements—iron, aluminum, potassium, and silicon—are chosen in different cases as constant in amount. This shows that the supposition that any element is fixed in amount is erroneous. Evidently in each case in making the calculations the method has been to choose the element in which the loss has been the least, and by this to gauge the loss of the other elements. For any one of these elements it is highly probable that the loss in most instances is as great as or greater than the loss of this element where other elements are chosen as the standard.

For instance, when aluminum is taken as fixed the loss of the potassium ranges from 29 to 83 per cent. It is highly probable that in the case of the phonolite, where potassium is taken as fixed, the loss of this element is at least as great as the minimum, and it may equal the maximum. Therefore the percentages of loss of the other elements of the phonolite, given on page 512, are greater than estimated. On the average aluminum is the least soluble of the elements, and in those cases where it can be used as the standard the underestimates for the other elements may not be large; but the occasional very considerable loss of alumina in some instances—for example, a limestone (Table VII, p. 513), where the loss is over 11 per cent—shows that even where this element is taken as fixed there may be very considerable losses of it, and consequently corresponding underestimates of the losses of the other elements. For instance, in a diabase (column 1 of Table III, p. 509) the aluminum is taken as fixed and the loss of the iron oxide is calculated at 18.1 per cent. In column 2 of the same table the iron oxide is supposed to be fixed and the loss of the aluminum is calculated at 21.38 per cent. The facts probably are that there were heavy losses of iron and aluminum in both rocks, and that in each case the calculated loss is much too small.

It is therefore clear that even the large losses of the elements represented by the above tables are much too small. The amount of the error in a given case for a certain element is large in proportion as the element is relatively insoluble. For instance, in the phonolite, where the potassium is considered fixed, the loss in alumina is given as 1.60 per cent; but if the loss of the potassium is, for instance, 30 per cent—and it is probably more than this—the loss of the alumina was more than 30 per cent. But in the case of the sodium, the loss of which is calculated as 66 per cent, this amount may be considerably too small, but it can not be more than 100 per cent; hence the relative error is much less in this case. For instance, in the diabase (Table V) the loss of sodium, 98.57 per cent, is almost, and of potassium, 100 per cent, is quite, correct. Where the losses are given as small in the foregoing tables, therefore, it is probable that the calculated amounts are but a fraction of the real losses; but where the losses are given as large, the errors, while very considerable, are probably not so great proportionally, and the calculated amounts give a rough approximation to the minimum percentage of depletion of the rocks in these elements.

In order to show the calculated comparative losses of the six important elements, aside from aluminum, the following table is compiled for those rocks in which the calculation has been made upon the supposition that the aluminum is fixed.

Table showing calculated percentage losses of important elements on the supposition that the aluminum is constant.

	Potash.	Soda.	Lime.	Magnesia.	Silica.	Iron oxide.	Alumina.
Gneiss (column 1, Table II, p. 508)	83.52	95.03	100.00	74.70	52.45	14.35	0.00
Syenite (column 2, Table II, p. 508)	81.85	97.11	87.90	82.10	62.18	86.17	0.00
Diabase (column 1, Table III, p. 509)	29.15	12.83	25.89	21.70	18.03	18.10	0.00
Diabase (column 3, Table V, p. 511)	100.00	98.57	99.04	99.90	63.57	87.81	0.00
Basalt (column 3, Table III, p. 509)	61.69		84.53	74.10	32.99	50.17	0.00
Basalt (column 4, Table III, p. 509)	83.34	74.41	47.24	96.38	65.56	88.84	0.00
Diorite (column 1, Table IV, p. 510)	38.75	84.87	97.30	97.17	37.31	21.03	0.00
Pyroxenite (column 2, Table IV, p. 510)	47.05	0.00	44.45	76.19	43.58	41.48	0.00
Argillite (column 3, Table IV, p. 510)	77.95	99.64	100.00	28.16	57.57	8.78	0.00
Average [a]	67.70	70.31	76.26	72.27	48.14	46.30	0.00

[a] Averages of potash and soda made from eight tables, as in the fifth it is impossible to state relative amounts of K and Na.

From the above table it appears that the order of loss, reckoned by quantity, beginning with the greatest, is: Lime, magnesia, soda, potash, silica, iron oxide, alumina. Of the two alkalies, more of the soda is dissolved than the potash. Of the alkaline earths, while on the whole the lime is dissolved in greater amount, in some rocks more magnesia is dissolved than lime. One of the unexpected things shown by this table is the fact that the percentage loss in silica is more than one-half as great as the average losses of the alkalies and alkaline earths. When it is remembered that the average amount of silica in the original rocks is 48.7 per cent, and that the average of the alkalies and alkaline earths together is but 17.5 per cent of the total, it is clear that the loss of the silica is about the same as the entire losses of the alkalies and the alkaline earths together.

This is a very interesting conclusion, since it shows that a very erroneous impression prevails in reference to silica. It has been generally supposed that the rocks in the belt of weathering are not much depleted in this compound. On account of the extreme insolubility of crystallized silica or quartz, it has been supposed that the silica of a rock is exceedingly insoluble. For instance, Merrill says: "Silica, even in its most soluble form, requires 10,000 times its weight of water for solution."[a] Doubtless, under ordinary circumstances, quartz is but sparingly soluble, although, as shown in another place (see p. 848), even this form of silica is dissolved to some extent. But in the majority of instances a large part of the silica is present as a silicate, although of course quartz is also abundant. When the silicates are broken up by carbonation there is every reason to believe that the greater portion of the freed silica separates as silicic hydroxide or colloidal silicic acid, which is readily soluble. That this reaction takes place has already been shown (see p. 480) and that the silicic hydroxide is dissolved and abstracted from the rocks is shown by the tables already given. In the rocks in which the silica is largely as silicate and the alumina is taken as constant the calculated losses of silica are high—in gneiss, 52.45 per cent; in syenite, 62.18 per cent; in decomposed diabase and basalt, 18.03 to 65.56 per cent; in diorite, 37.31 per cent; in pyroxenite, 43.58 per cent, and in argyllite, 57.57 per cent. The average of these numbers is 48.14 per cent. It should also be remembered that these are underestimates, because they are based upon the

[a] Merrill, George P., Rocks, rock-weathering, and soils, Macmillan Co., New York, 1897, p. 238.

erroneous supposition that the alumina is not dissolved at all. Since in some of these rocks a part of the silica was present as quartz and the rocks are not completely decomposed, it is certain that much more than half of the silica of the silicates decomposed in the belt of weathering went into solution and was carried elsewhere by the underground solutions. The number of instances given is large enough to make it probable that they represent approximately the average fact as to the soluble nature of the freed silica in the belt of weathering. It is therefore no inference, but a fact proved by analyses, that the freed and dissolved silica of the belt of weathering furnishes an enormous and adequate supply of this compound for the induration of the rocks of the belt of cementation, explained on pages 617–640.

Another notable thing shown by the table on page 515 is the small range in solubility of the various elements. With some exceptions the usual range for all the important elements except iron is not greater than a ratio of 1 to 2. But in the case of iron the amount dissolved varies greatly and irregularly. Disregarding the wider variations and considering only the thoroughly decomposed rocks in which the variations in the amounts of the other elements are not great, the amount of iron dissolved varies from 14.35 to 88.84 per cent, a ratio of more than 1 to 6. Doubtless this great variability in the amount of iron dissolved is dependent upon the fact that the iron occurs in both the ferrous and the ferric forms. The former is much more readily soluble. When the iron is mainly ferrous one would expect that a large proportion would be dissolved; where ferric, a small proportion.

In conclusion it may be said that, in order to comprehend the amounts of the losses of the various elements in the belt of weathering, it is necessary that the amount of loss of the supposed fixed substances should be known, and the methods of calculation used, although a line of attack giving approximate results fails to convey a correct impression. Doubtless in many cases the supposed fixed element is reduced to one-half or even to one-third of the original amount. If this be true, it is evident that the percentages of losses given fall far below the facts. It is, of course, impossible that more than 100 per cent of any constituent shall be lost; but from this it does not follow that the volume of the residual material may not be an exceedingly small fraction of the original material. For instance, if in a given rock the losses of all the various elements were exactly proportional, the conclusion from the analyses would be that there had been no loss, and yet 0.90 or 0.99

of the constituent might have been abstracted, and thus the amount of residual material left be but 10 per cent or 1 per cent of the original amount. Doubtless even the latter shrinkage sometimes occurs in the case of the limestones. It is therefore manifest that all that the foregoing tables show is that the losses calculated for the elements are at least as great as given, and in many cases they are in all probability much greater. Probably more accurate calculations than have been made are possible by taking as the constant constituents the very difficultly decomposable accessory minerals. For instance, where zircon is present and is uniformly distributed through the rock the assumption that this mineral is constant would undoubtedly lead to closer approximation to truth than has been obtained on the hypothesis that the iron or aluminum, or both, are constant.

But in order fully to solve the problem of the amount of losses of the various elements, in addition to the facts given in the tables, we need to know the original mass of the material as compared with the resultant mass. If we could combine these data we could give a quantitative estimate of the loss of each of the elements due to solution in the belt of weathering. But as long as one of the two necessary factors of the problem is not ascertained, we know only that the losses of material are much greater than any method of calculation yet made would lead us to believe.

ORDER OF DECOMPOSITION OF THE MINERALS, AND THE END PRODUCTS.

From the relative amounts of losses of the various elements, as given on page 515, one may infer the relative rate of decomposition of the minerals. The alkalies sodium and potassium commonly occur together; the same is true for the alkaline earths calcium and magnesium; but neither of these rules is invariable. One would expect the heavily alkaline minerals to be decomposed most rapidly; next in order the alkaline earth minerals; next in order the ferromagnesian minerals; and lastly and least rapidly the heavily aluminous minerals. Of course this statement is only of the most general kind, since most of the abundant minerals may have as bases more than one of these groups. But in proportion as the alkali end of the series dominates, the minerals are soluble; in proportion as the aluminous end of the series is dominant, they are insoluble.

We thus have the explanation of the order of decomposability of the silicates. Among the common anhydrous minerals, nephelite-leucite minerals are the most readily decomposed Second in order of decomposability

are the olivines and similar minerals. The third group is the pyroxenes and amphiboles. Fourth is the biotite-muscovite group. The fifth and most difficultly decomposable important group is the feldspars. Still more difficultly decomposable are some of the subordinate silicates. Of these garnet, staurolite, tourmaline, andalusite, fibrolite, cyanite, and zircon are probably the more important. The decomposition of these minerals is a relatively slow process. The order given is that of relative decomposability. Garnet alters somewhat readily; zircon very slowly indeed.

While the above statements hold in a general way, besides the constituent elements, another very important factor enters into the rate of decomposition, viz, the acidity of the mineral. Thus the feldspars vary from orthosilicates to trisilicates. On this account the orthosilicate anorthite decomposes more readily than the trisilicates albite and orthoclase, notwithstanding the fact that alkalies are absent in the first and abundant in the second. For the same reason some of the basic feldspars decompose under some circumstances more readily than certain of the more acid pyroxene-amphibole and biotite-muscovite groups.

The more abundant relatively insoluble products of the first stage of the alteration of the anhydrous silicates may be classified into hydrous silicates and oxides. The hydrous silicates comprise (1) the kaolin group, (2) the serpentine-talc group, (3) the chlorite group, (4) the hydro-mica group, (5) the zeolite group, and (6) the epidote group. The oxides include (1) the gibbsite-corundum group, (2) the quartz group, and (3) the ferric iron group.

Under long-continued favorable conditions of the belt of weathering many of these hydrous silicates, which form in the belt of weathering or which migrate into the belt of weathering from the belt of cementation, are further modified and changed to simpler compounds. The hydrous silicates thus further altered comprise serpentines, chlorites, zeolites, and epidotes. These silicates, it may be noted, are minerals very characteristic of the belt of cementation. The serpentine alters into magnesite, quartz, iron oxide, and other compounds. The chlorite passes into gibbsite, magnesite, iron oxide, and quartz. The epidote passes into gibbsite and quartz. It is probable that the zeolites pass into kaolin, gibbsite, carbonates, and quartz. Of course, under the conditions of the belt of weathering, the carbonates, including most of the magnesite, are dissolved and removed.

Of the oxides in the original rocks, quartz is that of dominant importance; but hematite and magnetite are of consequence. Quartz is only slowly dissolved. Hematite may become slowly hydrated. Magnetite may be oxidized and hydrated. All of the iron oxides are very slowly soluble.

It therefore appears that the important end products in the belt of weathering, whether the original compounds are silicates, hydrous or anhydrous, or are oxides, are included in the following groups: (1) Kaolin group, (2) talc group, (3) gibbsite-corundum group, (4) quartz group, (5) ferric iron group, hydrous or anhydrous. These are the minerals which have become adapted to their environment and may therefore persist indefinitely, so long as the conditions remain those of the belt of weathering. The elements which constitute this group are but six in number. In order of probable abundance they are as follows: Oxygen, silicon, aluminum, iron, magnesium, hydrogen.

A sixth unimportant group is formed by the very difficultly decomposable minerals already mentioned—staurolite, tourmaline, andalusite, cyanite, fibrolite, and zircon, and to these should probably be added the additional rare difficultly decomposable minerals, such as diamond, casiterite, gold, silver, xenotime, monazite, etc.

The quartz is largely that which was originally present in the rocks as quartz. Watson notes this fact for the granitic rocks of Georgia. While the total loss of silica in the rocks varies from 10 to nearly 80 per cent, the residual products contain quartz granules similar to those in the original rocks, with little or no evidence of corrosion.[a] The loss is due to the decomposition of the silicates and the abstraction of the greater part of the liberated silica, as explained on pages 516–517. For the most part the other important minerals of the end series are secondary.

The foregoing minerals, by the processes of decomposition and solution, are concentrated in the belt of weathering in various proportions. Under one set of conditions one group of them may be dominant and others entirely subordinate. Ordinarily, for instance, the rare difficultly decomposable minerals mentioned are not noticeable, but if the original rocks contain an unusual amount of them they may become rather important. In some cases a single one of these minerals may become important or dominant. An excellent illustration of such a case is that of Iron Mountain,

[a] Watson, Thos. L., Weathering of granitic rocks of Georgia: Bull. Geol. Soc. America, vol. 12, 1901, p. 99.

Missouri. Here the country rock is quartz-porphyry, in which are veins of iron oxide. The quartz-porphyry was disintegrated, decomposed, and largely removed, while the iron oxide was concentrated on the surface of the mound, producing a residual mass composed largely of nodules and bowlders of ferric oxide in a matrix of residual clay.

Where the conditions for solution and removal of the soluble material are not favorable, in addition to the end products above given there may be found important amounts of many other relatively soluble minerals. This condition of affairs, as explained on pages 497–498, frequently occurs in arid and semiarid regions, where in the residual soils are found considerable quantities of carbonates, sulphates, chlorides, and nitrates of the alkalies and alkaline earths.

These ultimate products of weathering are found to the exclusion of other compounds only where the process is complete, and this is very exceptional. Even under very favorable conditions of weathering the limit of disintegration is never attained and decomposition is usually far from complete. The end products of weathering are found as preponderant constituents only in the soils and subsoils in humid warm regions, which are permeated by plants; and even in these soils it is rare indeed to find all the constituents fully changed to the ultimate products above given. In proportion as the process of weathering is incomplete, other minerals and compounds are present; and it has already been seen that all kinds of rocks may exist in all stages of disintegration and decomposition. Hence the chemical composition of the rocks of the belt of weathering may vary most widely. Ordinarily the undecomposed or partly decomposed materials are prominent or even predominant. The undecomposed minerals are likely to be present in the order of their refractoriness. Therefore, the end compounds above given adapted to the belt of weathering may vary from a very subordinate quantity to an amount which vastly preponderates over all other constituents. While this is true, it is perfectly clear that the sum total of the processes of weathering tends toward mineralogical and chemical simplicity. The end products of weathering comprise but a few of the mineral species, and these species are simple compounds of a few elements.[a] Hence the propriety of the assignment of this belt to a zone of katamorphism.

[a] Merrill, George P., Rocks, rock-weathering, and soils, Macmillan Co., New York, N. Y., 1897, pp. 265–266.

TOTAL GAINS AND LOSSES IN WEATHERING, AND CHANGES IN VOLUME.

The processes of oxidation, carbonation, and hydration involve great additions of material and expansion in volume, provided all of the compounds formed remain. Of these expansions in volume, that due to hydration is the greatest. The added material is of course oxygen, carbon dioxide, and water. The increases in volume due to the processes of oxidation, carbonation, and hydration and their various combinations have been worked out for each of the minerals (see Chapter V), and the results are brought together in Table D on pages 395–408. It is seen there that the expansion of volume with most of the silicates due to these processes and their combinations usually varies from about 20 to 60 per cent, but in some cases is 80 per cent or more.

However, the processes of oxidation, carbonation, and hydration are accompanied by solution of great quantities of materials, and consequently the amount and the volume of the residual solid compounds are usually far less than those of the original compound because of the abstraction of a large proportion of the majority of the elements originally present and their transfer to the surface waters or to the belt of cementation.

As already fully noted, the calculations as to losses of elements thus far made have been upon the supposition in a given case that one element is constant; but in most cases, as already explained, it is highly probable that a considerable portion of these elements also has been dissolved.

On this hypothesis Merrill has brought together a number of computations upon the total losses of various rocks at different stages of weathering. The calculated losses vary from 13.47 to 97.635 per cent. Supposing the iron constant, disintegrated and partly decomposed granite from the District of Columbia has lost 13.47 per cent; supposing the aluminum constant, a disintegrated and partly decomposed diabase from Medford, Mass., has lost 14.93 per cent; a diorite from Albemarle County, Va, 37.51 per cent; an argillite from Harford County, Md., 40.83 per cent; a diabase from Spanish Guiana, Venezuela, 39.51 per cent; a basalt from Kammer Bull, Bohemia, 43.96 per cent; an altered pyroxenite, now soapstone, from Harford County, Md., 52.46 per cent; a syenite from Arkansas, 55.28 per cent; a basalt from Crouzet, France, 60.12 per cent; an altered pyroxenite,

now soapstone, from Fairfax County, Va., 77.95 per cent; and supposing the silica constant, a Carboniferous limestone from Arkansas has lost 97.635 per cent.

Watson[a] has calculated the losses of various disintegrated and decomposed granites from Georgia, including granite, porphyritic granite, and granite-gneiss, and has found that the loss for the entire rock varies in different cases from 7.68 to 71.82 per cent[b] The losses are in all cases higher on the assumption that the Fe_2O_3 is constant than on the assumption that the $Al\ O_3$ is constant.[c]

So far as I am aware, computations have not been made as to the addition of the constituents oxygen, carbon dioxide, and water in the processes of weathering. Until this is done it is impossible to make approximately accurate quantitative statements as to the total amounts of original material and weathered material. It is still less practicable to make quantitative statements as to the relative volumes of the original and altered materials, since in this matter are involved not only the additions and subtractions of materials, but the specific gravities of the original and secondary materials and their states of aggregation. Undoubtedly the specific gravities of the resulting minerals are less, on the average, than the specific gravities of the original minerals. Also, the state of aggregation is in almost all cases less compact. Therefore, for a given amount of material the volume of the weathered products is greater than that of the original material. But notwithstanding the addition of material. the lessened specific gravity, and the looser state of aggregation, the losses of the original elements are so great, where decomposition has gone far, that there is no question that the volume of the resultant material is often diminished.

Among the cases of diminished volume, that of the formation of residual clay from limestone undoubtedly represents the maximum. The dominant constituent of the rock, calcium carbonate, has been almost wholly dissolved and removed. The few feet of residual material at the surface of limestones represents the alteration products of the noncalcareous

[a] Watson, Thos. L., Weathering of granitic rocks of Georgia: Bull. Geol. Soc. America, vol. 12, 1901, pp. 93–108.

[b] Watson, cit., p. 101.

[c] Watson, cit., pp. 106–108.

impurities. Whitney estimated that to make 1 meter of residual clay in Wisconsin requires 35 to 40 meters of limestone and shale.[a] This involves a diminution of volume of more than 95 per cent. The shrinkage of limestone is scarcely less strikingly shown by underground solution, as a result of which the surface becomes uneven and pitted and frequently honeycombed by caves. The process may go so far as to result in the irregular sinking of the surface. This condition is especially well illustrated by the limestone of Kentucky and by the honeycombed limestones of Lake Huron, described by Bell.[b]

In line with the above is the explanation by Rutley of the slight thickness and lenticular character of many beds of Paleozoic limestone.[c] He holds that the underground waters have dissolved much the greater portion of the limestones, and that these slight layers or lenses are but remnants of the original formations.

From this maximum diminution of volume represented by limestone there are of course all gradations to no diminution, and doubtless in some cases there is actual expansion of volume. If expansion of volume occurs it would be likely to be in rocks where the minerals are mainly silicates. From the figures given by Merrill and by Watson, it appears that the losses of the original elements in acid, intermediate, and basic igneous rocks vary from 14 to nearly 80 per cent. These losses, as already pointed out, would be partly compensated for by the addition of oxygen and water. Moreover, on account of the lower specific gravity of the secondary minerals and the looser state of aggregation, there would be considerable expansion of volume. Hence it appears probable that the decrease in volume in the case of the weathering of these igneous rocks commonly does not exceed 50 per cent, and from this the decrease may run down to zero, or even expansion of volume may take place, especially in early stages of alteration.

EMPHASIS AND RETENTION OF STRUCTURES AND TEXTURES.

The first effect of weathering upon structures and textures is to emphasize them so that they may be readily seen. Structures which may not be visible in fresh rocks may be strongly marked upon the weathered

[a] Hall, James, and Whitney, J. D., Geology of Wisconsin, vol. 1, 1862, pp. 121–125.

[b] Bell, Robert, Honeycombed limestones in Lake Huron: Bull. Geol. Soc. America, vol. 6, 1895, pp. 297–304.

[c] Rutley, F., The dwindling and disappearance of limestones: Quart. Jour. Geol. Soc., August, 1893, pp. 380–381.

surfaces. Textures which the eye can not discover become clearly apparent. Any variation in the hardness or solubility of the rock is shown by a ridgy structure. As a consequence, every variation in original and secondary structures and textures may be shown on a weathered surface. So nice is weathering in its selective power in disintegration and solution, that when the different unaltered rocks can not be discriminated the weathered forms are easily separable.

Some cases will be mentioned illustrating the above general statements. Frequently the rocks which when unweathered appear to be massive, in the belt of weathering develop a strongly marked cleavage or fissility—cleavage in the lower part of the belt of weathering and fissility in the upper part. This effect is so marked that often it is difficult to believe that the weathered and unweathered portions of the rock belong to the same formation. The unaltered rock may be so massive that it has only a rift which can scarcely be called cleavage. The weathered portion may be split up into leaf-like layers, scores of them within the breadth of an inch, so that the rock at once would be called a schist, while one would not think of applying the term schist to the massive phases.

In connection with the emphasis of schistosity, micaceous minerals are likely to become very conspicuous. In the weathered portion of some rocks it seems as if the mica is one of the most abundant of the minerals, while in the unweathered portion it is scarcely noticeable. Excellent illustrations of this are found in various places on the Piedmont Plateau. Perhaps one of the best is at Washington, D. C. Here the unweathered rock at various places is a very massive appearing, slightly cleavable granite or a somewhat dense schist, whereas the partly weathered portions are fissile mica-schists.

Where mechanical forces have not displaced the particles with reference to one another, a rock may be completely weathered in the sense that none of the original minerals remain, and yet perfectly retain the original structures and textures. This is beautifully illustrated by the decomposed diabase dikes in the Penokee district, which still perfectly retain the textures of diabases, and yet in composition some of them approach very closely to kaolin. Every original mineral has been completely altered. Other similar instances described by Merrill[a] are the decomposed gneisses and

[a] Merrill, George P., Rocks, rock-weathering and soils, Macmillan Co., New York, 1897, p. 264.

schists of the Piedmont Plateau which, where so soft as to be readily removed with the pick and shovel, still show all their textures and structures. Russell describes the Triassic conglomerate near Wadesboro, N. C., as showing every detail of the original rock, and yet it is so "completely decomposed that when moist it can be cut with a pocketknife through pebbles and matrix alike, as easily as so much potter's clay."[a] Potter describes the feldspar-porphyry of Iron Mountain as "so soft that it can easily be whittled away with the penknife or scratched with the finger nail; at the same time the original porphyritic *structure* of individual crystals scattered through the mass is beautifully preserved, and is even frequently more distinctly visible than in the original rock, owing to stronger contrasts of color in the kaolinized material."[b] The so-called tallow rock of the lead and zinc district of southwestern Missouri shows all the textures and structures of the original chert, yet is easily pared like tallow with the penknife.

OBLITERATION OF STRUCTURES AND TEXTURES.

In proportion as the mechanical forces are important in connection with decomposition the original structures and textures are apt to be destroyed because of the differential movement of the particles. Structures and textures are likely to be long preserved in cases of decomposition alone,[c] but are destroyed by decomposition and disintegration combined, since these act together at and very near the surface.

The final stage in the process of weathering is the destruction of all textures and structures and the production of soils and subsoils. Near the surface, after the various minerals are broken apart they are mixed with one another indiscriminately by the mechanical forces of freezing and thawing and by the work of plants and animals (see pp. 440–451), and they are decomposed by the chemical forces. Finally no definite structures and textures remain. The character of the surface soil is modified by its organic content. It may contain from a small percentage of organic material to a predominant amount of that material, as in the case of the peat

[a] Russell, I. C., Subaerial decay of rocks, and origin of the red color of certain formations: Bull. U. S. Geol. Survey No. 52, 1889, p. 16.

[b] Potter, W. B., The iron-ore regions of Missouri: Jour. United States Assoc. Charcoal Iron Workers, vol. 6, 1885, p. 25.

[c] Merrill, George P., Rocks, rock-weathering, and soils, Macmillan Co., New York, 1897, pp. 264–265.

deposits. There is every gradation from the fresh rocks deep below the surface, which do not well exhibit their structures and textures, through those in which structures and textures are brought out with great clearness by the process of weathering, to completely disintegrated and partly decomposed rocks constituting the soils, in which no structures and textures remain. The gradations of the process may be very well seen at many localities where there are sufficiently deep cuts on the Piedmont Plateau of the United States.

SURFACES OF WEATHERING.

Weathering is only one of the complex processes which have an influence upon the surface features of the land. Transportation and erosion are quite as important in this respect as weathering, or even more important. But certain features of the surface are largely due to difference in the rate of weathering. Wherever the rocks are heterogeneous they differ in their power to resist weathering. The more resistant rocks commonly constitute the elevations, and the less resistant rocks the minor features. This is true of both the major and the minor features. Illustrations of this principle of various kinds will be mentioned. One of the most common illustrations are elevations or ridges formed by dikes, which are often more resistant than the surrounding rocks. In other cases dikes are less resistant than the intruded rocks, and where the dikes once were may be found deep, narrow-walled depressions or chasms, which may be occupied by streams or, if along the shore, by the water of the ocean or lake. Basic dikes in the resistant gneisses furnish frequent instances of this. Beautiful illustrations are seen on the coast of New England, especially Maine.[a]

Another interesting case of an irregular surface due to weathering is produced by bowlders of disintegration. The process of rock decay follows along the planes of weakness, and especially along fractures, such as joints. When a rock is cut by various sets of intersecting joints the process of weathering goes on more rapidly at the corners of the rectangular blocks than on the sides, thus producing round masses which

[a] Lord, E. C. E., On the dikes in the vicinity of Portland, Me.: Am. Geologist, vol. 22, 1898, p. 338. Bascom, F., On some dikes in the vicinity of Johns Bay, Maine: Am. Geologist, vol. 23, 1899, pp. 275–280.

frequently simulate to a remarkable degree bowlders produced by water or ice erosion.[a]

On the Piedmont Plateau, at many places where there are good sections exposed, as in railroad cuts, one may see hundreds of these roundish bowlder-like masses in the midst of soft disintegrated material. Erosion carries away the soft material faster than the bowlder-like masses. The latter therefore accumulate at the surface, and finally produce a surface which presents the appearance of a "Felsenmeer." Such a surface has strewn over it innumerable bowlder-like masses, small and large, from those less than a foot to those many feet in diameter. Some of the largest masses are dome-like and of such magnitude that the name "mountain" has been applied to them; for instance, Dunn Mountain, in North Carolina. These masses, small and great, are at the surface simply as a consequence of fracturing, differential weathering, and differential erosion.

Bowlders of disintegration and mountains of disintegration have been described by Branner[b] as also occurring on a most extensive scale in Brazil. They are beautifully illustrated by the granitic mountains of southern California and other arid regions of the United States.

The innumerable bowlders in the till of the glacial deposits of America and Europe are believed by some to be largely bowlders of disintegration which were produced before the advance of the ice sheets. This explanation premises that before the time of the continental ice sheet the glaciated regions were weathered in a manner somewhat similar to that of the Piedmont Plateau.

In minor details the nature of the minerals present controls the character of the surface. In general, any surface long exposed to weathering is roughened, owing to difference in the solubility of the minerals, or to imperfect cementation, or to these and other causes combined. The minerals which protrude are usually those which are relatively insoluble. The order of solubility, and therefore of disappearance, is that given on pages 518–521. Very numerous illustrations might be given of the roughening of the surface of rocks as a result of the variable rate of solution of the constituents. One of the best illustrations is furnished by the nepheline

[a] Becker, G. F., Geology of the quicksilver deposits of the Pacific slope: Mon. U. S. Geol. Survey, vol. 13, 1888, pp. 68–72.

[b] Branner, J. C., Decomposition of rocks in Brazil: Bull. Geol. Soc. America, vol. 7, 1896, pp. 269–280.

syenites. The nepheline-syenite of the Wausau district of central Wisconsin has a peculiar, deeply pitted appearance, due to the complete solution of the nephelites at the surface.

A further case of irregular surface is furnished by the cherty limestones; the calcite is dissolved more rapidly than the quartz, and thus the weathered surface presents a series of ridges and hollows, giving a very rough, ridgy surface.

DEPTH AND DEGREE OF WEATHERING.

The belt of weathering has already been defined as extending from the surface to the level of ground water, and locally to some distance below the level of ground water. (See pp. 409–411.) Furthermore, it has been seen that the level of ground water varies from 0 to more than 300 meters below the surface.

Whatever the thickness of the belt of weathering, the conditions throughout this belt are favorable for oxidation, carbonation, hydration, and solution, and therefore for the chemical reactions of decomposition. But the conditions are far more favorable for decomposition at the surface than at the lower part of the belt of weathering. Disintegration is much more limited in extent. It is at a maximum at the surface, but decreases rapidly with depth, and at 10 meters below the surface is scarcely appreciable. While it is clear that reactions of weathering extend throughout the belt as defined, it is equally certain that the processes are at their maximum efficiency at or near the surface, and decrease in efficiency as depth increases. But in some cases the processes are very important to the bottom of the belt, even where of very considerable thickness. This is illustrated by limestone regions, in which minor openings or even extensive caves may form abundantly quite to the level of ground water, although this may be 100 or 200 or more meters below the surface.

As to degree or stage of weathering, rocks are ordinarily spoken of as "weathered" where they are very appreciably affected by the peculiar weathering processes. As already explained, there are all gradations, from no weathering to complete weathering. Both extremes are very rare, although it is common for geologists to speak of "complete weathering" without telling what they mean thereby. In regions where the conditions for weathering

are favorable and the forces and agents of weathering have been long at work, greater or less thicknesses of material in various stages of weathering have accumulated.

Some of the regions will be mentioned in which the weathering processes are far advanced. Perhaps one of the most striking illustrations of advanced weathering is furnished by various limestone regions. The destruction of limestones located in the belt of weathering occurs both at the surface and below the surface. Below the surface the process is mainly that of solution, and in many regions the same statement applies to the surface reactions. Solution below the surface is the chief cause of the porous, cellular, and cavernous character of limestone formations above the level of ground water. As a result of solution at the surface, residual clays are formed. Residual clays in limestone regions vary in thickness from a few centimeters to 7 meters or more. Chamberlin and Salisbury give the average thickness of the residual clay of the driftless area of the upper Mississippi Valley as more than 2 meters.[a] Whitney estimates the thickness of the clay in this same area as 3 meters[b] This he believed to correspond to an original thickness of from 105 to 120 meters of limestone and shale.

In regions of noncalcareous rocks advanced decomposition may extend to the depth of a score or more of meters. The comparatively late coast ranges of California at many places are much weathered. The weathering affects all the rocks, but to a different depth. The Montara granite in many places is disintegrated to a depth of 6 to 10 meters. The complete disintegration and advanced decomposition of the rocks of the Piedmont Plateau, from Pennsylvania to Georgia, is well known to have extended from a depth of 2 or 3 meters to nearly 30 meters. In Georgia, according to Spencer,[c] decomposition has gone on to some extent at a depth of 60 meters. Merrill says that in many places the Sierra Nevada granodiorites are disintegrated and partly decomposed to a depth of 60 meters.[d] Belt states that the igneous rocks of Nicaragua are decomposed

[a] Chamberlin, T. C., and Salisbury, R. D., Driftless area of the upper Mississippi Valley: Sixth Ann. Rept. U. S. Geol. Survey, 1885, p. 254.

[b] Hall, James, and Whitney, J. D., Geology of Wisconsin, vol. 1, 1862, pp. 121-125.

[c] Spencer, J. W., The Paleozoic group of northwestern Georgia: Geol. Survey Georgia, 1893, pp. 22–24.

[d] Merrill, George P., Rocks, rock-weathering, and soils, Macmillan Co., New York, 1897, p. 274. See also Merrill on extent of weathering, pp. 276–278.

to a depth of 60 meters.[a] The Transvaal granites, according to Furlonge,[b] are decomposed to a depth of 60 meters.

From maximum amounts of weathered material illustrated by the above regions there are all gradations to amounts almost inappreciable. Excellent illustrations of such regions are the areas of the Northern Hemisphere over which the latest ice incursion has taken place. Glaciated quartzites may retain the glacial striations with marvelous delicacy, microscopic striæ being perfectly preserved. Such igneous rocks as the granites, gabbros, and peridotites, and other families usually show only a mere skin of appreciably decomposed material, ordinarily but a fraction of an inch in thickness. The readily soluble limestones usually present planed, grooved, and striated surfaces which show comparatively little evidence of modification. The minimum weathering effects are found on the solid rocks which have a thin veneer of drift or soil. Where this veneer is thick enough to bury the rock surface below the frost line, the only weathering effects ordinarily produced are slight stains of decomposition on the surface and along the joints and other fractures. Where the topographic forms are more rugged, so that the rocks are more exposed to weathering, there has been pronounced disintegration, and the decomposition has also gone farther. While the latest drift shows much more evidence of weathering than the solid rocks, below the soil the weathering effects are surprisingly slight. The pebbles and bowlders commonly show planing, grooving, and striæ, and scarcely any evidence of decomposition. The marvelous freshness of this drift, which has been exposed to the weathering forces under favorable circumstances for thousands of years, perhaps tens of thousands of years, is to me the best evidence of the slowness of the complex process of weathering.

A comparison of the small amount of weathering in the glaciated regions with the great amount in some other regions gives one an idea of the vast amount of time required for deep and advanced weathering. Even if the most conservative estimate as to the length of time since the last ice invasion were used as a measure of the rate of weathering, it would follow that to have accomplished such weathering results as are exhibited

[a] Belt, Thomas, The naturalist in Nicaragua, p. 86.

[b] Furlonge, W. H., Notes on the geology of the Dekaap gold fields in the Transvaal: Trans. Am. Inst. Min. Eng., vol. 18, 1890, p. 337.

in the southern Appalachians, Nicaragua, and Brazil must have taken several or many hundreds of thousands of years. The process of decomposition was of course more rapid in these regions than in the colder northern regions, but even allowing for this the time required for the work accomplished must have been great.

RATE OF WEATHERING.

The rate of weathering depends upon all the factors that have heretofore been given. These factors may be classified under the forces and agents at work in weathering, the materials weathered, the thickness of the belt of weathering, and the stage of weathering.

FORCES AND AGENTS AT WORK IN WEATHERING.

The rate of weathering is rapid in proportion as the temperature is high; the humidity is great; erosion by wind, water, and ice is active; and plants and animals are abundant. All these statements have been so fully developed on previous pages that they will not be further amplified here.

MATERIALS WEATHERED.

The rate of weathering as dependent upon the material involves a consideration of the chemical composition of the rocks, the mineral composition, and the closeness of aggregation.

CHEMICAL COMPOSITION.

In general the more basic a rock the more rapid the rate of weathering, and the more acid a rock the less rapid the rate of weathering. As to individual elements, the following statements may be made: The richer a rock is in alkalies the more rapid is the rate of weathering. With a given quantity of alkalies, the greater the proportion of sodium the more rapid the alteration, and the greater the amount of potassium the less rapid the alteration. The greater the amount of alkaline earths the more rapid is the alteration. With a given quantity of alkaline earths, the greater the proportion of calcium the more rapid the alteration, and the greater the proportion of magnesium the less rapid the alteration. The greater the amount of iron the more rapid is the alteration. The greater the amount of alumina the less rapid is the alteration. Where the iron and aluminum

mutually replace each other, the greater the proportion of aluminum the more rapid the alteration. The greater the amount of silica the less rapid is the alteration.

MINERAL COMPOSITION.

The readiness of the alteration of minerals is largely a direct consequence of the character and the chemical composition. With a given chemical composition, the greater the proportion of glass the more rapid the alteration, and the greater the proportion of crystallized minerals the slower the alteration. Among the crystallized minerals, the greater the proportion of the easily decomposed minerals the more rapid the alteration.

The order of decomposition of the common anhydrous minerals from the easiest to the hardest, as given on pages 518–521, is (1) nephelites and leucites, (2) olivines, (3) pyroxenes and amphiboles, (4) biotite-muscovite group, (5) feldspars, (6) garnets, staurolite, tourmaline, andalusite, cyanite, and (7) hematite, magnetite, and quartz.

STATE OF AGGREGATION.

Fine-grained rocks weather less rapidly than coarse-grained ones. This is a consequence of the closer interlocking of the mineral particles of the fine-grained rocks, and of the fact that the differential expansion and contraction by change of temperature is less with fine particles than with coarse particles. The more open the aggregation the more rapid the alteration; the closer the aggregation the less rapid the alteration. This follows from the fact that openings give ready access to the agents of alteration, and the border of every opening is a place of attack for the chemical agents, and therefore all classes of openings promote decomposition. The openings in rocks are divided into pore spaces between the mineral particles, sheet openings, and irregular openings (see p. 129). Pore spaces are generally in the mechanical sediments, the lavas, and the tuffs; therefore mechanical sediments, lavas, and tuffs alter much more rapidly than the plutonic igneous rocks and the compact metamorphic rocks. Sheet openings are of various kinds, such as faults, joints, bedding partings, and fissility. All these openings serve as channels through which the waters may readily pass and extend the decomposing effect. In general, along a fault or a joint, decomposition extends more rapidly downward than in the adjacent solid rock. Where

the openings are fine and close, as in the case of fissility, the process extends downward uniformly and much more rapidly than where this structure is absent.

As examples of very fine- and close-grained rocks which weather less rapidly than other rocks of similar chemical and mineral composition may be mentioned the Berlin rhyolite-gneiss and the Niagara limestone of Wisconsin. The former has a maximum crushing strength of 3,304 kg. per sq. cm. and the latter a crushing strength of 2,812 kg. per sq. cm.[a] These are probably the highest crushing strengths yet recorded for such rocks. While altogether unlike in composition and origin, they are alike in their remarkable uniformity, fineness, and closeness of grain. Many of the marbles are not more porous than the limestone mentioned, but the mineral particles are much larger, and in this difference probably lies the explanation of the very unusual strength and slow weathering of this limestone.

From the above there follows the conclusion that in proportion as the aggregation is coarse and open the rate of weathering is rapid; in proportion as it is fine and close the rate of weathering is slow. These general statements need modification with reference to disintegration through freezing and thawing (see pp. 441–442).

THICKNESS OF THE BELT OF WEATHERING.

Since the entire belt of weathering is affected by the reactions characteristic of that belt, the greater the thickness of the belt the more effective the process of weathering. It has already been explained that, other things being equal, the level of ground water is likely to be a considerable depth below the surface in proportion as the elevation is great. It therefore follows that the rate of weathering is greater in elevated than in low regions. This is partly a direct consequence of the fact that the weathering agencies have a greater volume of material upon which to work. But probably even more important than this is the rapid removal of weathered material in elevated regions. Material disintegrated and partly decomposed by the weather is removed by erosion as rapidly as formed, and therefore continuously exposes new surfaces to the agencies of weathering.

[a] Buckley, E. R., Building and ornamental stones of Wisconsin: Bull. Wisconsin Geol. and Nat. Hist. Survey No. 4, 1898, pp. 360–363.

While the above is true, if one were to confine his attention entirely to the decomposing effect of the weather and exclude disintegration, it is probable that there is a limit beyond which increase in elevation decreases the decomposing effect. As explained on pages 499–500, 502–503, great elevation gives conditions unfavorable for the existence of life, and life is one of the necessary agents in rapid decomposition.

While the reactions of weathering are taking place throughout the entire belt above the level of ground water, the process is at its maximum efficiency near the surface and rapidly decreases in efficiency with depth. This is largely due to the fact that life is confined to the upper few meters and therefore the decomposing effects of life rapidly diminish with depth.

It is a corollary from the relation of the thickness of the belt of weathering and the rate of the process that geological periods in which there are extensive land areas at a high elevation above the sea are periods in which the processes of weathering are most rapid. These processes are essential to the rapid formation of all classes of sediments, including the limestones. The relations between weathering and sedimentation are discussed on pages 555–560.

STAGE OF WEATHERING.

Where the rocks in the belt of weathering are fresh, and therefore have not been adapted to their environment, the processes of weathering are active. And, per contra, where the processes of weathering have transformed the rocks to minerals adapted to the belt of weathering the processes are slow. For instance, the conditions are favorable for rapid weathering in glaciated regions where all the weathered products have been recently removed, and where, therefore, the rocks and minerals are not adapted to the belt in which they are found. In such areas as the Piedmont Plateau, on the contrary, where in some places the minerals have been very largely transformed to those characteristic of the belt of weathering, and are therefore permanent under the conditions of that belt, the processes of weathering are very slow.

Probably where weathering is in an early but not the earliest stage the processes are at their maximum activity. Where by changes of physical conditions rocks have been brought into the belts of weathering, at first the conditions are very unfavorable for the existence of life, and the great rôle

which life plays in weathering has already been pointed out. But when the processes of weathering have gone so far that a good soil has formed and abundant life has taken possession of the little weathered rocks, the conditions for weathering, including disintegration and decomposition, are probably most favorable.

DISTRIBUTION OF DISSOLVED MATERIALS.

We have seen that all the elements of the rocks are dissolved, but with exceedingly variable rates, and that in consequence of this there is a concentration in the belt of weathering of a few minerals and fewer elements. Where only the end products of weathering are present the important elements there concentrated are but six in number—oxygen, silicon, aluminum, iron, magnesium, and hydrogen. Before taking up the question of what becomes of the dissolved materials, it is advisable to recall the elements dissolved, their relative rates of solubility, and the fact that under ordinary conditions of weathering and erosion but a portion of any of the elements in the belt of weathering are rapidly dissolved.

It has been seen (p. 518) that the common bases are taken into solution in the following order:

(1) The alkalies. Of these the sodium minerals are more readily decomposed than the potassium ones and hence a much greater amount of sodium than potassium is dissolved.

(2) The alkaline earths. Of these the calcium minerals are certainly more readily decomposed than the magnesium minerals, and therefore calcium is taken into solution in much greater quantity than magnesium.

(3) Iron, especially that in the ferrous form.

(4) Aluminum, which, while dissolved to a less extent than the other bases, is dissolved in large amounts.

It has also been seen (p. 485) that the dominant acids which go into solution are silicic and carbonic. Common subordinate acids in solution are hydrosulphuric, sulphuric, nitric, hydrochloric, and phosphoric. In volcanic districts hydrofluororic and hydrobromic acids are frequently present.

Within the zone of observation by far the greater quantity of the substance is carried as carbonate, and, as is well known, the salts are usually not carried as normal carbonates but as bicarbonates.[a]

---

[a] Letts, E. A., and Blake, R. F., The carbonic anhydride of the atmosphere: Sci. Proc. Royal Dublin Soc., new series, vol. 9, pt. 2, 1900, p. 160.

It must also be recalled that the dissolved silicic acid is in the colloidal state, and in the belt of weathering is an inactive chemical agent, and therefore is not united with the bases in solution. The acids in the solutions in combination with the bases therefore do not include silicic acid. Of the remaining acids carbonic is that of dominant importance.

It is further to be recalled that the amounts of the various bases and acids which may be taken into solution are dependent not only upon their relative strengths, but also upon the amounts present and upon the combinations in which they exist.

We are now prepared to take up the question as to what becomes of the materials dissolved in the belt of weathering. These materials are abstracted by plants, transported to the belt of cementation, permanently abstracted by the run-off, and dissolved, transported, and reprecipitated in the belt of weathering.

MATERIAL ABSTRACTED BY PLANTS.

Considerable quantities of the soluble constituents produced in the belt of weathering are abstracted by the plants and built into their bodies. Of the bases, the plants take greater quantities of the alkalies than of the alkaline earths. They take only minute amounts of iron and aluminum. The acids abstracted by plants in important amounts are nitric, phosphoric, and silicic. In this connection it should be remembered that under ordinary conditions the amount of alkalies available is less than that of the alkaline earths, and that the amounts of nitrates and phosphates available are far less than the amount of silicic acid. Therefore, even if the amounts of these compounds abstracted by the plants were the same, this would result in the abstraction of a considerable portion of the alkalies and the nitric and phosphoric acids, while the major portion of the alkaline earths, of the iron and aluminum, and of the silicic acid would remain.

The distance of the transfer of material in the belt of weathering by means of plants is limited by the depth to which roots extend. It has been noted (pp. 445–446) that the roots of ordinary grains and grasses extend into the soil 1 or 2 meters, and that the roots of larger plants may extend to a depth of 10 meters. The vertical transfers are therefore to be measured by these distances. The amount of material transferred by plants is a direct function of the luxuriance of the vegetation. Luxuriant vegetation occurs

where humidity is high, and hence it is in the humid regions that vertical transfers of material through the agency of plants is greatest in quantity.

It will be remembered that by far the greater portion of the plants either decay or are used by animals, which in turn ultimately decay. At the time of decay the mineral material dissolved by the plants either passes into the run-off and is transported to the sea or else joins the soil, to be there again redistributed. Probably the latter is the larger portion. Therefore much of the soluble material abstracted by life from the belt of weathering is but temporarily held. The only permanent loss to that belt is the portion which gets into the streams and thence into the sea.

Since the part of the vegetation above ground to a large extent decays at or near the surface, the permanent effect of the vegetation in the transportation of the dissolved material is to bring it from a depth of one to several meters below the surface near or to the surface.

The roots decaying in situ to some exteut redistribute the material and transfer it toward the surface, but not to so great a degree as the portion of the plants above the ground with the help of the roots.

MATERIAL TRANSFERRED TO BELT OF CEMENTATION.

A large amount of material which is dissolved in the belt of weathering is carried downward by the descending waters and joins the subterranean sheet below the level of ground water. It will be shown below and in the following chapter (pp. 612–617) that the material which joins the belt of saturation is again subdivided, a part being precipitated in the belt of cementation and a part joining the surface waters and thus being transported to the sea.

MATERIAL PERMANENTLY ABSTRACTED BY RUN-OFF.

A considerable amount of the soluble material of the belt of weathering joins the run-off. In times of abundant rain water flows over the surface. This water takes up the soluble material with which it comes into contact. The amount dissolved is especially likely to be considerable if abundant rains follow a time of drought, for it will be seen below that in times of deficient rain capillarity brings the soluble salts to the surface where they can be readily abstracted by the run-off. From seepage waters and springs the streams receive large quantities of water from the belt of

cementation, containing soluble material derived directly or indirectly from the belt of weathering. In so far as the streams empty into lakes with no outlet the material is not permanently lost to the belt of weathering, but rejoins it, as will be shown below. But the vast majority of streams reach the ocean and the dissolved material of the run-off is contributed to the mother water. The material thus contributed is the source of the salts of the sea.

MATERIAL DISSOLVED, TRANSPORTED, AND REPRECIPITATED IN BELT OF WEATHERING.

A portion of the compounds dissolved in the various ways in the belt of weathering is transported to other parts of the belt and precipitated. The salts which are reprecipitated depend upon (a) the abundance of the compounds, (b) their relative and changing solubility, and (c) the humidity of the region.

(a) The more abundant a compound is in a solution the more likely is it to be reprecipitated. This law is almost self-evident, for the more material there is in solution the more likely, under the changing conditions which obtain in the belt of weathering, are the solutions to become supersaturated and thus precipitation take place. The supersaturation may result from any of the causes given on pages 113–123. This principle of precipitation of the abundant compounds is one of the utmost importance in metamorphism. It applies not only to the belt of weathering but to all belts and zones, and is correlative with the principle already explained, that the more abundant a substance is the more likely it is to be dissolved. Both are but special cases of the law of mass action. (See p. 94.)

Both of these principles are well illustrated by the solution and precipitation of calcium carbonate in the limestone regions, although the relative solubilities of the compounds present also enter into the result. Where the dominant material is calcite or dolomite, or any combination of these, these materials preponderate in the underground solutions. Also to an equal degree they preponderate in the precipitates. The extensive solution of limestone has already been considered. (See pp. 485–486). But wherever there is a minute cavity, a cleft, a cave, or an opening of any other kind in limestones in the belt of weathering, there calcite, aragonite, or dolomite, or some combination of these, may be precipitated. The small

cavities may be lined with crystals of nearly the composition of the surrounding rock, thus producing geodes; the joint, fault, and irregular openings may be partly or completely filled with carbonates, producing veins; but geodal filling and veins commonly form in the belt of cementation. In the caves the floor is ordinarily covered with stalagmites and from the roof stalactites depend. The precipitation of the carbonate in the openings is commonly caused by the lessened pressure, by the escape of some of the dissolved carbon dioxide, or by evaporation, any one of which or any combination of which may produce a condition of supersaturation and consequent deposition.

Another compound which is very abundantly precipitated in the belt of weathering is silica, as opal, chert, or quartz. This again is largely a consequence of its abundance, but also is a function of its solubility. (See p. 480.) By the decomposition of the silicates silicic acid, probably largely as colloidal silicic acid, is set free in almost incredible quantities. (See pp. 480, 516–517.) The larger amount of this material probably joins the belt of cementation, and thus is a source of the silicification which is so dominant a process of that zone. (See pp. 622–623.) But by chemical change, which is a factor in its precipitation as well as in its abundance, a very considerable amount is partly or completely dehydrated and thrown down in the belt of weathering as opal or quartz. Like calcite and dolomite, it is deposited in the belt of weathering in geodal cavities, in caves, and in veins, and as siliceous sinter.

(b) The more insoluble a compound is, the more likely is it to form a precipitate in the belt of weathering. This is almost self-evident, and only needs cases illustrating the principle. The best illustrations are furnished by the iron and aluminum oxides and their mixtures. It has already been seen that these are the two compounds which are most frequently taken as constant in weathered rocks, and on this hypothesis are used to determine the amount of loss of the other constituents. Much of the iron in the original compounds is in the ferrous form, but under the conditions of the belt of weathering it is oxidized to the ferric form, and much of it simultaneously precipitated. On account of the insolubility of the oxide of iron and oxide of aluminum, as compared with other constituents, a large amount of iron, as hematite, limonite, and other hydrated forms, and of alumina, both hydrous and anhydrous, and of mixtures of iron oxide and aluminum oxide, bauxite, accumulates at the surface. It is well known

that iron is abundantly transported as a carbonate, and aluminum as a sulphate, as in the natural alums. Also, both the alumina and the ferric oxide may be partly transported to the places of precipitation as aluminates and ferrates.[a]

What proportions of these materials have been dissolved and precipitated and what parts are simply residual undissolved substance is probably not usually determinable, but in many places solution and reprecipitation appear to be the chief cause of the concentration. Not infrequently these concentrates are so rich in iron and alumina as to be ores. This phase of the matter is much more fully developed on pages 842–846 and pages 983–989.

As much less abundant important insoluble compounds which accumulate under the same principle as iron oxide may be mentioned the manganese oxides, pyrolusite, manganite, etc. The abundant precipitation of quartz in the belt of weathering, as explained on page 540, while largely due to its plentifulness, is also controlled in an important degree by its relative insolubility.

Still another set of compounds which well illustrate the principle are the phosphates. It is well known that the manufactured soluble phosphates used as fertilizers largely "revert" or are transformed to relatively insoluble phosphates, and as such are precipitated in the soil.[b]

(c) To a certain point the less humid a region the more likely are precipitates to form in the belt of weathering. The reason for this is obvious. If the amount of rainfall be so small that it is largely brought to the surface by capillary and other forces, as explained on pages 419–423, and evaporated, the material it holds in solution will be precipitated; but if a region be so arid that there is not sufficient precipitation to dissolve material abundantly, it can not be abundantly precipitated. Indeed, it has been seen (pp. 496–498) that in regions of extreme aridity disintegration is the rule and decomposition takes place only to a small extent. Therefore we conclude that the climatic conditions for abundant precipitation of minerals in the belt of weathering are those of moderate rainfall for a certain period of the year, with aridity for the remainder of the year.

---

[a] Cameron, F. K., Application of the theory of solutions to the study of soils: Rept. Div. of Soils, U. S. Dept. Agric., No. 64, 1899, p. 169.

[b] Wyatt, Francis, The phosphates of America, Scientific Pub. Co., New York, 1892, pp. 22–26.

In the arid regions not only are the relatively insoluble compounds precipitated in the belt of weathering, but the readily soluble compounds may likewise be thrown down, such as the salts of the alkalies and alkaline earths. These elements may be combined with any of the acids which exist in the soils. Thus there may be precipitates of such soluble salts as the alkaline carbonates, and even the alkaline chlorides and nitrates. The more abundant salts precipitated are sodium, potassium, calcium, and magnesium carbonates, sulphates, and chlorides. Nitrates and borates of the bases mentioned are also locally abundant. In any given case the bases and acids unite in such a manner as to produce the most insoluble compounds. Therefore the carbonic acid first unites mainly with the alkaline earths and is thrown down as calcium and magnesium carbonates. Where sulphuric acid is present it unites mainly with calcium, producing gypsum. The hydrochloric and nitric acids are left for the alkalies. Frequently the salts and acids may not be present in proportion to combine as above. For instance, after the alkaline earths are exhausted by the sulphuric and carbonic acids there may be residual carbonic acid which will necessarily unite with the alkalies. Or again, on the contrary, the sulphuric and carbonic acids may not be sufficiently plentiful to exhaust the alkaline earths, and under such circumstances chlorides of calcium and magnesium may form. This is well illustrated by the calcium chloride deposits of the borders of Great Salt Lake, where locally there is as much as 40 per cent of this material.[a]

The compounds are likely to be precipitated in the openings of the rocks, where evaporation may occur. Such openings are, of course, by far the most abundant in the soils at and near the surface, and decrease in abundance with depth. Therefore it is in the soils that the greatest amount of precipitation takes place, but below the soils are found joint cracks, bedding partings, caves, etc., and in such openings deposits of the various compounds mentioned are built up. While in these openings the precipitation is largely dependent upon the abundance of the solutions and their evaporation, and also upon the abundance of the various salts and their relative solubilities, in exceptional cases the reactions may not be simple chemical ones, but be largely or wholly dependent upon animal life. This is illustrated by certain caves where abundant phosphates and nitrates are

[a] Gardner, F. D., and Stewart, John, A soil survey in Salt Lake Valley, Utah, Rept. Div. of Soils, U. S. Dept. Agric., No. 64, 1899, p. 113.

attributed to the excrement of bats.[a] But, as already said, the preponderant precipitates of the belt of weathering form in the soil.

The accumulation of particles at and near the surface in the soil is a matter of great geological and agricultural importance, and therefore this case will be especially considered.

CONCENTRATION AT AND NEAR THE SURFACE.

The abundance of alkalies throughout the soils of the semiarid regions of the United States and other parts of the world is well known. The soil for large areas is impregnated with considerable amounts of alkaline salts. Of these salts sodium and potassium chlorides, carbonates, and sulphates are the most important. Where the amount of alkaline carbonates and sulphates in the soil exceeds one-half of 1 per cent crops can not be grown.[b] Where more than one-tenth of 1 per cent is as carbonate or as "black alkali" crops can not be grown. But locally in arid regions, as, for instance, at places near Salt Lake, the amount of sodium carbonate is as much as 10 per cent.[c] In some regions nitrates of the alkalies are not less important than the chlorides, sulphates, and carbonates. The country most noted for abundance of nitrates is Chile, where there are extensive deposits. Muntz and Marcano believe that these nitrates were produced by the action of nitrifying bacteria in the humid regions, that the salts have been transported by water to the area where now found, and that the evaporation of this water has resulted in the deposition of the nitrates.[d]

The concentration of soluble products in the soil is accomplished both by underground and by overground circulations.

CONCENTRATION BY UNDERGROUND CIRCULATION.

The concentration of considerable quantities of soluble material at and near the surface may be accomplished by the circulation of the ground water. This circulation may be confined to the belt of weathering or may include the circulation in the belt of cementation.

---

[a] Hess, Wm. H., Origin of nitrates in cavern earths: Jour. Geol., vol. 8, 1900, pp. 129–134. Nichols, H. W., Nitrates in cave earths: Jour. Geol., vol. 9, 1901, pp. 236–243.

[b] Means, T. H., and Gardner, F. D., A soil survey in the Pecos Valley, New Mexico: Rept. Div. of Soils, U. S. Dept. Agric., No. 64, 1899, pp. 53, 74.

[c] Gardner, F. D., and Stewart, John, A soil survey in Salt Lake Valley, Utah: op. cit., p. 113.

[d] Comptes rendus Acad. Sci., Paris, vol. 101, 1885, pp. 65–68. See, also, Merrill, George P., Rocks, rock-weathering, and soils, Macmillan Co., New York, 1897, pp. 372–373.

CONCENTRATION BY CIRCULATION MAINLY CONFINED TO BELT OF WEATHERING.

It has been seen (pp. 419–423) that of the water which enters the belt of weathering a considerable portion returns to the surface through molecular attraction and vegetation and is evaporated. During the journey of water downward and upward, in the outer belt of water circulation, it takes material into solution.

When the water, the circulation of which is wholly confined to the belt of weathering, or which is derived from the belt of cementation by molecular attraction, nears the surface evaporation begins, and finally a state of saturation is reached. Ordinarily saturation occurs only within a few inches of the surface, and especially in the outer inch or half inch. For instance, in a case of segregation of saline incrustation at Washington, D. C., Cameron states that practically all of the salt was in the surface inch, the larger part of it being in the top eighth inch.[a] As a result of the above processes the soluble materials in the outer part of the earth are taken into solution in large quantities and brought near or to the surface and there deposited. (See pp. 539–543.)

It has been seen (pp. 417–419) that the downward movement of the water is due both to gravity and to molecular attraction, and that the upward movement is due largely to molecular attraction, working against gravity. It is well known that the soil, even in humid regions, is relatively rich in soluble constituents. This is undoubtedly in large part explained by the fact that the soluble products are mainly produced by the process of decomposition, and are more largely manufactured within the soil than elsewhere, as so fully set forth on previous pages. The material there manufactured is strongly held by the water of imbibition. But Means suggests in this connection that the failure of the downward-moving water in humid regions to remove the excess of soluble material is due to the fact that the downward movement is mainly in large openings, the force being gravity, and is therefore rapid, and consequently only a relatively small amount of material is taken into solution, while the upward movements are in the smaller openings, mainly under the influence of molecular attraction, and consequently this upward-moving water is loaded with material.[b]

---

[a] Means, Thos. H., On the reason for the retention of salts near the surface of soils: Science, new series, vol. 15, 1902, p. 33.

[b] Means, cit., pp. 33–35.

The upward transfer of material, while largely due to the water which does not pass beyond the belt of weathering, is also partly due to water which under the influence of molecular attraction passes upward from the sea of ground water. The amount of such water increases in proportion as the surface of ground water is near the surface. It has already been pointed out (pp. 419–422) that when the ground water is comparatively near the surface a very large amount may thus migrate upward and be evaporated. This material carries with it all the salts which it had in solution in the belt of cementation and such as it may take into solution during its upward movement above the level of ground water. Locally, as a result of over-irrigation, seepage from irrigation ditches or unusual precipitation for several years, the level of ground water may be raised. A layer of the belt of weathering may be thus encroached upon. This belt is likely to contain a large amount of soluble material. To illustrate, Hilgard states that "The investigations of the California station have shown that in the arid region few uplands normally contain less than from 2,000 to 2,500 pounds [900 to 1,300 kilograms] of soluble salts per acre in 4 feet [1.22 meters] depth, and much more has been found in the silty substrata of the Salton Basin in southern California even to 22 feet [6.7 meters] depth." When the level of ground water is raised this material is abundantly dissolved by the water. If the rise continues so that the level of ground water is within 3 meters or less of the surface, a very large amount of salts may be carried upward to the surface from the belt of cementation by molecular attraction.[a]

The solutions carry more of the readily soluble compounds than of the difficultly soluble ones, and therefore the substances transferred in greater amounts are the alkalies and the alkaline earths. In humid regions the material thus transferred to the surface layer is largely taken into solution at times of abundant precipitation and carried downward again. Therefore, if there be no change in the composition of the compounds, there is little accumulation of such material near the surface. But in the semi-arid and arid regions, where the belt of weathering is comparatively rich in alkalies and alkaline earths, the material carried upward during the long periods of drought may not be compensated by downward transfer at the rare occasions of abundant precipitation. Consequently the upper part of the soil may become exceedingly rich in salts of the alkalies and alkaline earths,

[a] Hilgard, E. W., The rise of alkali salts to the soil surface: Science, new series, vol. 15, 1902, pp. 314–315.

especially the former. Indeed, the surface may thus become saturated with these salts.

The process of migration of alkalies to the surface is well illustrated in various irrigated districts. Before irrigation the soil may have contained only a sufficient amount of alkalies to be very fertile. In many districts, by irrigation for some years, so large a quantity of alkalies has been brought to or near the surface as to injure vegetation or even to make crop growing impossible. Where the water used is sweet, these effects follow from over-irrigation. Where more than a sufficient amount of water is used a part of it passes to some depth below the surface. Between the times of flooding a part of this is brought to the surface by capillarity, carrying with it various dissolved salts. Also by continual seepage from canals at higher levels water passes below the surface, and by capillarity is brought to the surface in the cultivated areas, carrying with it dissolved salts. As the water evaporates these salts are precipitated in the soil. This process is cumulative, and after a number of years, as already stated, the quantity of alkalies may become so great as to lead to the abandonment of formerly productive tracts. This process is well illustrated in San Joaquin Valley, California, and in Salt Lake Valley, Utah. At the latter place alone Whitney states that of the 50 square miles once irrigated about 10 square miles, or one-fifth, has become unfit for agriculture.[a]

Where the waters used for irrigation are themselves very rich in alkalies, as, for instance, in Pecos Valley, New Mexico, the accumulation of alkalies in the soils is prevented in a different way, namely, by very abundant use of water with considerable intervals between and by thorough underdrainage. By this method the salts which are precipitated between the periods of irrigation by evaporation are dissolved by the abundant waters at the time of irrigation, and thus accumulation of the alkalies in the soil is prevented.[b]

While the more readily soluble constituents are of far more importance as precipitates at or near the surface than the less soluble salts, the latter are precipitated in the soils. Of these difficultly soluble compounds silica and ferric oxide are perhaps the only ones of sufficient importance to require mention.

Many sandstones which have long been exposed to the weather have a

---

[a] Whitney, Milton, Field operations of the Division of Soils: Rept. Div. of Soils, U. S. Dept. Agric., No. 64, 1899, p. 25.

[b] Whitney, Milton, cit., pp. 22–24.

thin outer layer or crust of quartzite. Sections of such material show that it is a true cementation quartzite. (See pp. 865–868.) Casehardening also occurs in many other kinds of rocks, for instance, granite. In the production of casehardening the waters have penetrated to a greater or less depth, and through capillarity have been brought back to the surface as a result of drying of the outer surface.

During the journey of the water silica is dissolved, probably mainly in the colloidal form. This H_4SiO_4 is doubtless largely that liberated from the silicates during the process of carbonation. (See pp. 473–480.) Probably the solutions do dissolve some silica from chert and quartz and bring it to the surface, but the amount of this is probably small as compared with that transported in the colloidal form. It therefore appears that the process of surface cementation, so far as the cement is silica, is a correlative of the process of carbonation.

Very near the outer surface of the rock the water evaporates, the silica is dehydrated, and quartz is deposited. In this case chemical change takes place. The silica is thrown down in a very difficultly soluble form; so that even in humid regions the falling water is unable to dissolve the quartz and carry it downward. This process may continue until the sandstone, which may be loose or almost incoherent below the surface, is a quartzite at the surface. The casehardened layer may be a mere outer film but a fraction of a centimeter in thickness, perhaps one-half to one-fourth of a centimeter. In other instances the casehardening may extend to a depth of a centimeter, or even several centimeters. Ordinarily the maximum induration is at the surface, and the transitions between the indurated and soft parts of the rocks are somewhat rapid. This fact gives positive evidence that evaporation and consequent deposition are at a maximum at the surface.

Casehardening has been observed in many parts of the world. It is beautifully illustrated at many points in the arid region of western United States. In arid regions the hardened film has frequently been smoothed by the wind-blown sand, so as to present a polished surface. Such polished hardened films are known as "desert varnish." While more common in arid regions, casehardening has been found in humid regions. For instance, the phenomena are well exhibited by the Potsdam and St. Peter sandstones of Wisconsin.[a]

---

[a] Wadsworth, M. E., Some instances of atmospheric action on sandstone: Proc. Boston Soc. Nat. Hist., vol. 22, 1883, p. 202.

Surface induration, while most common as the result of the deposition of silica, is not limited to this compound. The upward-moving solutions carried by molecular attraction may, under favorable circumstances, contain iron salts in solution. When the solutions approach the surface evaporation takes place and the iron salts are thrown down, usually as limonite or hematite. If precipitated as limonite, this compound may be later dehydrated and hematite be formed. Where the iron salts are transported as carbonate, oxidation takes place at the time of precipitation. While it is not necessary to suppose that the iron is always transported as carbonate, since limonite and hematite are so insoluble it is natural to suppose that in most cases the iron is transported in some other form than the oxide, and is chemically changed when precipitated. By the above processes we have surface induration due to iron oxide cement. This is beautifully illustrated at various places in the desert regions of western United States. One of the best localities known to me is that of the volcanic rocks of the Colorado Desert east of Needles along the line of the Santa Fe Railway. The desert is strewn with bowlders of disintegration, of a light-colored lava. The part of these bowlders embedded in the sand has its normal color; the part above the sand line is a rich reddish brown, due to hematite, the iron of which has been brought to the surface in solution and has there been oxidized and precipitated.

Another interesting case of the segregation of iron oxide at the surface is furnished by quartzite bowlders in the Potsdam sandstone of the driftless area of the Baraboo district of Wisconsin. Here, locally, in consequence of weathering processes, the sand matrix has been carried away and the quartzite bowlders have accumulated at the surface. The quartzite is ferruginous, containing hematite, which gives purplish and brownish tones to the unweathered rock. The centers of the bowlders still show these colors; the borders are rich yellow-brown, or red, due to limonite and hematite, the color being much more marked than in the centers of the bowlders or in the massive quartzite, and plainly showing an unusual proportion of the iron oxide. Between the outer surfaces of the bowlders and the central cores of unaltered quartzite are frequently bands, from two to five centimeters broad, almost white, which fade off into the heavily ferruginous outer parts of the bowlders and to the less ferruginous cores. It is very clear in these cases that the iron oxide once in this lighter middle

band has been taken into solution, transferred to the surface, and there deposited. It is a depleted area, and correlative with it is the surplus of iron oxide at and near the surface. This case is interesting, since the iron, both in its original form and where segregated, is an oxide. It is therefore clearly shown that iron in the form of hematite is soluble in the belt of weathering. Whether actually carried in that form or whether reduced and changed to carbonates or other salts at the time of transfer is uncertain.

In a similar manner other cements besides silica and iron oxide may be brought to the surface and deposited. These processes, while most prominent at the surface, are not limited to it; they take place to a considerable extent along the major openings of the rocks near the surface, such as joints. Crosby has noted the induration of Pikes Peak granite along the joints. Surface induration of granite, rhyolite, and other rocks has been noted, the casehardening materials ordinarily being the three most common ones—silica, iron oxide, and calcite.[a]

In connection with casehardening it is interesting to note the influence of the so-called quarry water contained in stones taken from the quarry. This is the water of imbibition. As this water is evaporated the material in solution is deposited between the grains near the surface and thus helps to cement them. The very considerable induration thus produced by the quarry water is evidence that this water is rich in mineral solutions. In this deposition of material we have the explanation of the great advantage of dressing sandstones and other porous rocks before the quarry water is lost by evaporation.

From the previous pages it appears that capillarity is most effective in transferring soluble material from below the surface to the surface in semi-arid and arid regions. But if in regions which are ordinarily known as humid there are seasons of drought, great quantities of soluble material may be segregated at the surface by capillarity. So far as this material is thrown down in a readily soluble form it is likely to be largely taken into solution at times of abundant rainfall and again carried below the surface. But if at the time of precipitation chemical change takes place, so that the material is transformed to a relatively insoluble form, as, for instance, the dehydration of colloidal silicic acid forming quartz, or the oxidation of iron

[a] Merrill, George P., Rocks, rock-weathering, and soils, Macmillan Co., New York, 1897, pp. 254–256.

carbonate, forming hematite or limonite, its solution is very slow, and thus the upward transfer of the compounds at the time of drought may more than compensate for the solution at periods of humidity, and actual segregation of certain materials at the surface take place.

Furthermore, it is to be noted that in humid regions vegetation is abundant, and therefore the upward transfer of material through the agency of life is at a maximum. This compensates in part for the relative inefficiency of capillarity in humid regions as compared with that in arid regions. It therefore appears that whether a region be arid or humid the vertical transfer of soluble material through the agency of life and by capillarity takes place effectively.

CONCENTRATION BY CIRCULATION EXTENDING INTO BELT OF CEMENTATION.

It has been pointed out, on pages 128, 156, that waters continuously join the belt of cementation and continuously issue from it. In general the waters which issue from the belt of cementation are not saturated, but not infrequently the waters of springs as they near or reach the surface precipitate material by lowering of the temperature, by evaporation, or by chemical change.

Perhaps one of the most common deposits thus produced is limonite. The iron precipitated is usually carried underground as carbonate, but when it reaches the surface, where oxygen is abundant, oxidation takes place, the carbon dioxide is liberated, the ferric oxide unites with water, and limonite is thrown down. Thus bog deposits of iron ore are built up. Another deposit which is not infrequently produced is calcium carbonate. This may be thrown down as a result of lessening pressure and temperature, or by evaporation. Such deposits are known as tufa or travertine. They are found in many parts of the world. One of the best illustrations is furnished by the travertine deposits of the Yellowstone National Park, at Mammoth Hot Springs and on Terrace Mountain. The latter represents the deposit of springs now dead. A third class of deposits thus built up by issuing spring water is siliceous sinter. These are best illustrated by the deposits of geyserite in the Yellowstone National Park. It is interesting to note that the travertine and the siliceous sinter deposits in the Yellowstone Park are in the same region, and one in which the spring waters are hot. To the latter fact may be attributed the magnitude of the deposits.

Such waters were capable of taking more calcium carbonate and silica into solution than ordinary cold underground waters. An interesting fact in connection with these deposits is the correlation of their character with the rocks adjacent. As pointed out by Hague, the calcareous deposits of Mammoth Hot Springs and Terrace Mountain are adjacent to sedimentary rocks which contain abundant calcium carbonate to serve as a source of supply.[a] The geyserite deposits of siliceous sinter, on the other hand, are in a region of volcanic igneous rocks, mostly rhyolite, and where there are no sedimentary rocks. Here calcium carbonate is not available, but silica is very abundant in natural glass and in crystallized minerals. These silicates are decomposed by the processes of weathering. Colloidal silicic acid is thus formed, which is readily taken into solution by the hot waters and abundantly brought to the surface. There dehydration, partial or complete, takes place and the geyserite deposits are built up.

In these cases it is clear that the major portion of the material deposited was derived from the solid rocks through which the hot solutions circulated, rather than from the magmas which heated the water, as maintained by some. (See pp. 1033–1034, 1071–1072.)

CONCENTRATION BY OVERGROUND CIRCULATION.

The waters of streams and lakes always contain soluble material derived from the soil dissolved by the run-off and from the lower part of the belt of weathering and the belt of cementation by the issuing spring waters. The material dissolved by the run-off may form in the soil by the processes of weathering or be brought to the surface by means of life or by the underground circulation. The amount of this material is comparatively small in humid regions, but is relatively large in arid regions. In some arid regions the amounts held by the surface waters may be so great as to unfit them for domestic purposes, or even for purposes of irrigation, since, as already noted, a comparatively small amount of alkali is sufficient to prevent plant life.

The best illustrations of overground concentration are furnished by basin regions, where there is no permanent run-off. In the United States the Great Basin is the one of dominant importance. Southern California also contains basins of great extent. Into the Great Basin a large number of

[a] Hague, Arnold, Geological history of Yellowstone National Park: Trans. Am. Inst. Min. Eng., vol. 16, 1888, pp. 795–796.

streams flow, some of them of considerable size, for instance, the Bear, Ogden, and Weber rivers. The smaller streams which flow into the basin for the most part rise on the mountain slopes of the Wasatch and Sierra Nevada, which wall the Great Basin on the east and the west. Within the Great Basin there are many mountain ranges, some of them of great size. The greater of these are the Humboldt and the Inyo ranges. On these basin ranges many streams rise and flow down upon the floor of the basin. The precipitation in the Great Basin region is mainly in the winter and spring. At times of abundant precipitation and rapid melting of the snow many ephemeral streams form upon the floor of the basin itself. The streams, small and great, all fail to reach the ocean; the larger of them flow into the permanent lakes of the basin, such as Great Salt Lake, Mono Lake, and Winnemucca Lake, but by far the greater number flow into the ephemeral lakes. These lakes, which are numbered by hundreds, are shallow; they may be many miles across in early spring and entirely disappear before autumn. Also, the permanent lakes, like Great Salt Lake and Winnemucca Lake, greatly expand at the time they receive the large contributions from the streams and shrink during the summer and autumn. All the streams bring their contributions of soluble materials to the lakes and, in addition, the usual amounts of mechanical sediments. Hence there is mingled in the Great Basin lakes the greatest variety of materials. The salts of alkalies, the salts of the alkaline earths, and lesser amounts of other soluble salts are all commingled with one another and with the mechanical sediments.

When the waters of the ephemeral lakes are evaporated, all the materials held in solution and in suspension are thrown down. In the larger of the ephemeral lakes there is a distinct tendency for the chemical and mechanical sediments to be deposited in alternate layers. Within a short time after the flood season of spring the mechanical sediments are largely laid down. During the dry season the lake evaporates and the chemical sediments are precipitated. These sediments, while perhaps partly dissolved by the waters of the lake of the succeeding flood season, are largely buried under the mechanical sediments of that year. Upon these mechanical sediments follows the next layer of chemical sediments, and so on.

It is difficult for one who has not traveled in the Great Basin region to appreciate the vast amount of alkaline material deposited by the ephemeral

lakes. In journeying across the desert of Nevada in summer or autumn a person is rarely out of sight of one or more areas, small or great, varying in size from a fraction of an acre to hundreds or even thousands of square miles, covered with the almost snow-white chemical deposits of the evaporated lakes, which glare with intense light under the brilliant sun.

The permanent lakes, like Great Salt Lake, continually receive supplies of material in solution and are constantly being evaporated. When such lakes were first formed the salts steadily accumulated until the water became saturated. After a state of saturation is reached each year at the flood season chemical deposition may and usually does cease and solution even may take place to some extent. After the flood season the mechanical sediments quickly subside. During summer and autumn evaporation greatly exceeds the influx of water; the lakes shrink; the solutions become supersaturated and chemical precipitation follows. Along the borders of the permanent lakes chemical and mechanical precipitates are interstratified the same as in the ephemeral lakes; but in the central areas of these lakes, beyond the depth to which plentiful mechanical sediments are carried, the chemical precipitates, comparatively little contaminated with mechanical material, are steadily built up. It is well known that the annual rainfall is not uniform, but that there are periods extending over a number of years of more than and less than the average rainfall. It is in the dry parts of the cycles that the thick deposits of chemical sediments are largely built up. The formation of such deposits is now also promoted in many lakes by the use of the water in irrigation.

As already noted, the abundant chemical sediments are the alkalies and alkaline earths, carbonates, sulphates, and chlorides. The order in which the materials are deposited depends upon the relative amounts of these substances and upon their relative solubilities. In consequence of difference in solubility there is a more or less marked tendency for the bases first to unite with the acids so as to produce the most insoluble compounds. Thus the calcium and magnesium unite with carbonic acid to produce marl and tufa. The calcium unites with sulphuric acid to produce gypsum. But always before one substance is completely precipitated one or more others begin to be thrown down, and consequently there is a mingling of precipitates. This is especially true of those compounds which are closely allied chemically, such as the calcium and magnesium carbonates, the sodium and potassium chlorides, etc. While there is a tendency for

the most insoluble compounds first to be thrown down, these relatively insoluble compounds may be very sparse in quantity, and therefore more soluble salts be first precipitated. While all the above complications make the result very uncertain, still there is usually a marked tendency to stratification, each stratum being composed dominantly of one compound or of two closely allied compounds. Thus a stratum may consist mainly of marl, another mainly of gypsum, another mainly of common salt, and so on.

By great changes in the humidity of a region and some changes perhaps in the topographic conditions a basin lake may become smaller or wholly disappear, thus baring its deposits to the ordinary forces of erosion. Such lakes are Lake Bonneville, described by Gilbert, and Lake Lahontan, described by Russell. The chief chemical deposit of Lake Bonneville, according to Gilbert, was a white calcareous marl. However, this marl is very impure, containing a large amount of silicates and silica, in one case as much as 74 per cent.[a] The chief chemical deposits of Lake Lahontan, according to Russell, are a calcareous white marl and tufa. The white marl, like that of Bonneville, is impure, containing about 30 per cent of silica, alumina, and iron, of which 22 per cent is silica. The tufa deposits are mainly calcium carbonates, although small amounts of magnesium carbonates and other constituents are contained.[b] It appears that Lakes Bonneville and Lahontan did not become saturated with the salts of the alkalies. In the case of Bonneville this stage was not reached until it had shrunk to Great Salt Lake.

By still more radical topographic revolutions and changes in meteorological conditions than those experienced by Bonneville and Lahontan, deposits of salt lakes may become deeply buried below other sediments, and thus we have the explanation of the salt, the gypsum, and other similar deposits of various parts of the world.

DISTRIBUTION OF RESIDUAL MATERIALS.

The distribution of the dissolved material in the belt of weathering is of very great importance, but the distribution of residual material which at no time goes into solution is of no less importance. The concentration

[a] Gilbert, G. K., Lake Bonneville: Mon. U. S. Geol. Survey, vol. 1, 1890, p. 202.

[b] Russell, I. C., Geological history of Lake Lahontan: Mon. U. S. Geol. Survey, vol. 11, 1885, pp. 152–153, 203.

of this material and its transportation, separation and deposition by the epigene agents of erosion ought, perhaps, to be considered here; but this is a subject so large and complicated that it is ordinarily given a separate treatment in physiography; therefore no attempt will be here made even to summarize this part of the cycle of the movements and alterations of the material of rocks. The residual undissolved material of the belt of weathering is a source of the mechanical sediments and the partial source of the combined mechanical and organic or chemical sediments.

This residual material is deficient in the elements which have been taken in solution in large amounts; it is therefore complementary to the dissolved material. It follows that the residual material which is the source of the mechanical sediments is likely to be deficient, to a varying extent, in the alkalies and the alkaline earths, and of these it is much more likely to be deficient in sodium and calcium than in potassium and magnesium. This is true without taking into account the mechanical sorting. So far as there is mechanical sorting, there may be deficiencies or excesses of other elements. But it may here be suggested that the deficiency in certain elements, as compared with the original rocks, furnishes an adequate reason why the mechanical sediments, when metamorphosed, do not reproduce mineral combinations like those of the original rocks. The metamorphosed equivalents of the mechanical sediments will naturally be deficient in minerals rich in sodium and in calcium, such as sodalite, nephelite, anorthite, etc.

RELATIONS OF BELT OF WEATHERING TO SEDIMENTARY ROCKS.

BELT OF WEATHERING THE SOURCE OF SEDIMENTARY ROCKS.

The materials transported to the sea in suspension and in solution by overground and underground waters, and subordinately by the wind and ice, supply the materials for the sedimentary rocks. These materials are almost wholly derived, directly or indirectly, from the belt of weathering. The main source of the sedimentary rocks is therefore the belt of weathering. The material derived from the belt of weathering is transported in suspension and in solution.

MATERIAL TRANSPORTED IN SUSPENSION.

The dominant constituents of the sedimentary rocks transported in suspension are the minerals produced in and adapted to the belt of weathering and the slowly decomposable minerals. The first class comprises the kaolin group, the serpentine-talc group, the chlorite group, the zeolite group, quartz, iron-oxide minerals, and aluminum-oxide minerals. Of the second class the minerals of dominant importance are quartz and the acid feldspars. Quartz is included in both classes, and is the mineral of greatest abundance in the sedimentary rocks; second to it is feldspar. With the abundant minerals there are present, of course, very subordinate amounts of the very difficultly decomposable minerals, such as garnet, staurolite, tourmaline, zircon, etc.

The readily alterable minerals are usually rare or subordinate in quantity in the sediments. The group of minerals most readily alterable, the feldspathoids, including nephelite, leucite, and sodalite, are rarely, if ever, found in the sedimentary rocks. Minerals of the olivine group are also rare in the sedimentary rocks. The ferromagnesian group of minerals, including the pyroxenes, amphiboles, and biotites, are more difficultly decomposable and are frequently found; still, they alter with such readiness that they are generally subordinate in quantity, although locally abundant. While where decomposition has been important the above are the dominant minerals in the mechanical sedimentary rocks, in many sedimentary rocks the materials are but slightly decomposed, disintegration being the chief process of destruction of the original rocks. In mechanical sediments derived from disintegrated material, as already pointed out, all or nearly all the original minerals may be present. Where disintegrated materials are dominant the rocks produced by their consolidation are conglomerates, arkoses, and grits. As would be expected, there is every gradation between rocks in which decomposed material is important and rocks in which disintegrated material is dominant. Therefore, sedimentary rocks may be built up of materials which, in chemical composition, stand anywhere between decomposition products and disintegrated products, and which vary from the mineralogical simplicity of the former to the mineralogical complexity of the latter. Since the chemical analyses of such materials vary greatly, as shown by the analyses given on pages 507–515, it is usually possible, by the analysis of a sedimentary rock, to obtain a rough idea as to the stage of

decomposition. In cases where both the decomposed and the undecomposed materials are abundant the mineralogical complexity is even greater than in the ordinary original rocks.

Even where decomposable minerals are largely altered and the abundant minerals are few, by different combinations of these few minerals a wide variety of sedimentary rocks may be produced. This is due to the opposing processes of mingling of the materials in streams and separation of them by waves and currents. Where material is deposited at the mouth of a great and rapid river all the minerals are intermingled; where the material is contributed to the sea no faster than it can be sorted by the waves and the currents the different minerals are separated. Between thorough assorting and no assorting there are all gradations. In proportion as the material is unassorted the combinations of different minerals and of different-sized particles built into a deposit is varied; in proportion as the process of assorting is advanced a deposit is likely to be built up of a single mineral or of a combination of two or more minerals having approximately the same size and the same specific gravity, or at any rate which are floatable to the same degree. Where the materials are slowly contributed to the sea and are long subjected to the waves, the nearly perfect assorting, both as to mineral material and as to size, is remarkable. As an illustration of nearly perfect assorting may be mentioned the St. Peter sandstone of Wisconsin. This sandstone is almost wholly composed of quartz grains, analyses showing it to have 96.74 per cent of silica[a] Moreover, the variation in diameter of the great majority of the grains is less than by ratios of 2:3 (pp. 861–862).

MATERIAL TRANSPORTED IN SOLUTION.

It has been pointed out that the material transported in solution is mainly composed of the more soluble compounds, viz, salts of the alkalies and the alkaline earths. The ocean as a whole is not saturated with the salts derived from the belt of weathering, nor is there any evidence that it has been so at any time in the past, although locally inclosed seas and lagoons do become saturated, and in this case chemical precipitation may occur precisely as in inland lakes, described on pages 551–553. But the dominant precipitation of material from solution in the ocean is not through the process of chemical precipitation, but through the agency of life. As is

[a] Geology of Wisconsin, vol. 2, 1878, p. 680.

well known, by far the most abundant of all the constituents thus precipitated is calcium carbonate. The corals and other shell animals abstract this material from the water and build it into their hard parts. As the animals die this material is deposited, and thus great limestone formations are built up, and doubtless have been in the past. No adequate reason has been given for the belief that great seas connected with the ocean have become saturated by calcium carbonate so as to build up limestone formations by chemical precipitation, although, as already intimated, chemical precipitation of calcium carbonate has locally occurred. While the chief precipitation of calcium carbonate is through the agency of life, chemical replacement works in conjunction with organic precipitation. No sooner is a deposit of calcium carbonate formed than the other salts of the sea begin to act upon it, under the laws of heterogeneous systems, and thus modify the deposit. Calcium is taken in solution and is replaced by the other bases, especially by magnesium. (See pp. 798–802.)

MATERIAL TRANSPORTED IN SUSPENSION AND SOLUTION.

Commonly the material transported in suspension and that transported in solution are built into deposits which are largely separated from each other; but not infrequently both classes of material are laid down together, and this causes additional variety in the sedimentary rocks. We thus have sediments built up of all proportions of materials mechanically transported and materials chemically transported. It therefore appears that the sedimentary rocks may have a wider variety of chemical composition and of mineral composition than any of the igneous rocks. But while this is possible, the rule for the great sedimentary formations is simplicity, and this is due to the tendency toward simplicity in the belt of weathering and to the processes of assorting. The first great process of assorting in the belt of weathering is the subdivision of material into insoluble compounds transported in suspension and soluble compounds transported in solution. As already pointed out, the mechanical sediments are commonly assorted by waves and currents, and the chemical sediments are assorted by life; and thus the dominant formations of the sedimentary rocks are simple, both chemically and mineralogically. This is especially true of the two kinds of formations, sandstones and limestones. The shales, arkoses, graywackes, and conglomerates represent the varieties of sedimentary rocks in which there is greater complexity.

ROCKS PRODUCED FROM MATERIAL OF BELT OF WEATHERING WITHOUT TRANSPORTATION TO THE SEA.

While by far the larger part of the material produced by the processes of weathering is transported to the sea, either in suspension or solution, the weathered material may be buried under other deposits without transportation to the sea. The weathered material not carried to the ocean may be classified into residuary and transported material. Such deposits may be from a few meters to hundreds of meters, or, in the case of the transported material, even a thousand meters in thickness. After a deposit of residuary or transported material has accumulated, the sea may transgress over the region so quietly as not to disturb the larger part of the weathered rock. As an example of the burial of residuary material under marine deposits may be mentioned the Coastal Plain of the United States. Here the deeply disintegrated pre-Cretaceous rocks have been overridden by the ocean, and upon them have been laid down the Coastal Plain deposits. If the sea should now advance over the Piedmont Plateau somewhat rapidly part of the deeply disintegrated and decomposed belt there occurring might be buried under marine deposits without disturbance.

Weathered material may be transported a greater or less distance, but not to the sea, and thick deposits be built up. This is well illustrated by the deposits of the Great Basin region of the United States. Here the weathered material, instead of being transported to the sea, continuously accumulates in the lower areas. This has gone on until there are hundreds or a thousand or more meters of weathered rock material, which has accumulated between the mountains. Some of this material is deposited by the streams; other parts are deposited by the ephemeral lakes; others by the permanent lakes. (See pp. 551–554.) The result is the building of great sedimentary deposits, in which there is local assorting. When the sea next encroaches upon this Great Basin area there may be buried below the marine deposits a great mass of weathered material, which differs radically from the ordinary marine deposits in that there has been comparatively little abstraction of soluble salts, and which therefore must have nearly the same average chemical composition as the original rocks from which they are derived, but not the same mineral composition.

The residuary or transported material, when sufficiently deeply buried, whether below the sea or by upbuilding, as in the Great Basin area, passes

into the belt of cementation, and may even pass into the zone of anamorphism. It may be metamorphosed in those positions, and produce rocks different in character from ordinary metamorphosed sedimentary rocks, because the material has a different chemical composition. It is pointed out in another place (see pp. 831–833) that the jaspilites of the Lower Huronian of the Marquette district represent a weathered belt, which has been overridden by the Upper Huronian seas, deeply buried by later sediments, and metamorphosed under the conditions of the zone of anamorphism.

TRANSITION BETWEEN BELT OF WEATHERING AND BELT OF CEMENTATION.

Before taking up "The belt of cementation," it will be well to call attention to the fact that the belts of weathering and cementation are not sharply separated, but there is a transition between them. In many cases the explanation of the transition is partly that locally strong downward currents carry solution as a preponderant process well below the level of ground water, and partly that a considerable quantity of oxygen may be carried some distance below the level of ground water and produce reactions characteristic of the belt of weathering. In other cases the level of ground water rises and falls, as explained on pages 423–429, and therefore there is a belt in which the conditions are alternately those of the belt of weathering and the belt of cementation. While in general the transition from one belt to the other is somewhat gradual, in some instances it is rather abrupt. An excellent illustration of an abrupt change is that given by Culver in the case of the diabase in Minnehaha County, S. Dak.[a] This rock is thoroughly disintegrated and apparently much decomposed to a depth of 6 or 8 meters, that is, to the bed of the stream which marks the limit of ground water. Says Culver: "The limit of decomposition seems to be marked by the position of the stream; the rock in its bed is firm and apparently unaltered."

As an illustration of a transition belt of considerable width may be cited the iron-ore deposits of the Lake Superior region. Many of these deposits extend from the surface to a depth of 200 to 500 or more meters, but at the greater depths they usually become gradually smaller and less rich in hematite. The level of ground water is rarely deeper than 30 meters.

[a] Culver, G. E., and Hobbs, William H., On a new occurrence of olivine-diabase in Minnehaha County, South Dakota; Trans. Wisconsin Acad. Sci., Arts, and Letters, vol. 8, 1888–1891, pp. 206–207.

These iron-ore deposits consist mainly of hematite with some limonite, and occasionally some magnetite, with silica as the main impurity. In passing downward the silica is likely to become somewhat more abundant, and finally the ores become too lean for working. As explained in another place, these ores have been precipitated in pitching troughs on impervious basements by downward-percolating waters which bear oxygen, often at places where the rocks have been much fractured by orogenic movement and are therefore very open and porous. Simultaneously with the precipitation of the iron oxide silica is dissolved. (See pp. 1193–1197.) It appears, therefore, in the case of these ore deposits, that oxidation and solution, both reactions characteristic of the belt of weathering, have locally extended for 300 meters or more into the belt of cementation.

CHAPTER VII.

THE BELT OF CEMENTATION.

BELT OF CEMENTATION DEFINED.

The belt of cementation, like the belt of weathering, belongs to the zone of katamorphism. The belt has been discussed from the physical-chemical point of view in Chapter IV. From this point of view its definition is very similar to that of the belt of weathering. It is a belt in which the reactions take place with liberation of heat and expansion of volume, or come under the first part of van't Hoff's law. From a geological point of view the condition of affairs is very different in the belt of cementation from that in the belt of weathering, and it is primarily the purpose of this chapter to consider the belt of cementation from this point of view, but, as heretofore, the geological treatment is subject to the general principles which have been developed in the previous chapters.

Geologically the belt of cementation may be defined to include that part of the zone of katamorphism which is below the belt of weathering. It has as its lower limit the zone of anamorphism, the zone in which permanent openings, whether produced by fracture, original sedimentation, or any other cause, are of subcapillary size. It is bounded above by the belt of weathering, the lower limit of which is the level of ground water. All of the classes of openings described on pages 129–146 are found in this belt. But whatever the nature of the openings, whether cracks and crevices produced by mechanical action, such as those of joints, faults, bedding partings, and fissility, or the openings originally present in the rocks, such as pore spaces of the mechanical sediments and the vacuoles in volcanic rocks, they are usually filled with water.

The belt under discussion is named the "belt of cementation" because cementation is the most obvious and probably the most important single process of the belt. But it is by no means the only process; it will be seen

that metasomatism, injection, consolidation, and fracturing are important, and some of them scarcely less so than cementation. The geological evidence clearly shows that no sooner are openings produced in this belt, or rocks containing openings transferred to this belt, than deposition of material in the openings begins and continues until the separated parts are firmly cemented. Since cementation is only one of the processes which occur, the name "belt of cementation" is less fortunate than the name for the belt at the surface, the belt of weathering, for weathering is a general term properly covering many, if not all, the processes which take place within the belt to which it is applied; but as there is no comprehensive term available, the name "belt of cementation" has been chosen, with hesitation, on the basis of naming the belt by the most obvious and characteristic of the processes which take place within it. In many respects the name "belt of induration" would be a good one, since under quiescent conditions the rocks are hardened by the various processes at work. The process of cementation also hardens or indurates many of the rocks. This name would cover both of the chemical processes, cementation and metasomatism, and the igneous process of injection, but it is contradicted by the mechanical process of fracturing. It is more comprehensive than the name "belt of cementation," but is inaccurate in that induration is not always characteristic of the belt. The name "belt of saturation" well covers the fact that the openings are commonly filled by water solutions, but this is also true of the exceedingly minute openings of the zone of anamorphism. Furthermore, the term "belt of saturation" would be likely to be understood to imply that the solutions in the belt are always saturated with the compounds with which they are in contact, and this is far from the truth. Certainly the term "belt of cementation" is the one which seizes as distinctive the most characteristic and obvious feature, evidences of which are seen in the field in all major openings, and which are equally evident through the microscope in minor openings.

The geological evidence that cementation is the universal law for the part of the zone of fracture in which the rocks are usually saturated with water seems to be conclusive. In mining operations the world over it has been found that there is a tightening of the ground when the level of ground water is reached. Above that level the rocks are likely to be open and porous, giving the freest circulation to the waters of the belt of weathering;

but below that level the rocks are usually much less porous, although it does not follow that the water circulation may not be important and rapid. Fine illustrations of the sudden lessening of the pore space at water level are furnished by the lead and zinc districts of the Mississippi Valley. This lessening of the pore space is partly due to the solution of material above the level of ground water, rather than to cementation below it. But observations below the level of ground water show that cementation is as certain as is solution above. Sandstone formations, as is well known, are cemented mainly by silica, although calcium carbonate, iron oxide, etc., are subordinate cementing constituents. Wherever sandstones are found which have long been below the level of ground water, cementation has taken place, either by enlargement of the old grains or by independent deposition between the grains, or by the two combined. All stages of this process are seen, from those in which the grains have simply built out crystal facets that sparkle in the sun, to rocks so firmly cemented as to be perfect quartzites, in which fracture breaks through the cement and across the old grains rather than around them.[a] The pore spaces of arkoses, tuffs, and other rocks which have long been below the level of ground water, are shown by microscopical examination to have been also closed; but often the cements are more variable than in the case of quartzites, frequently including feldspar, pyroxenes and amphiboles, calcite, and various other minerals.

That cementation is the universal rule for the porous rocks below the level of ground water was ascertained only by microscopical study, but in the field may be seen evidence of cementation of the larger fractures. The filling of ancient joints, recementing the separated joint blocks, the filling of fault openings, thus producing true veins, and the cementing of the fragments of breccias are all well-known phenomena. Where rocks have been broken and buried deep enough to be below the level of ground water and have remained there long, it is found to be an almost universal rule that the filling of these larger openings has begun; and usually, so far as the older openings are concerned, the process has been practically completed, although recent earth movements may have produced openings which have not been closed.

The openings which are being filled in the belt of cementation vary in size from minute pores between the grains to great caves. Interesting

[a] Irving, R. D., and Van Hise, C. R., On secondary enlargements of mineral fragments in certain rocks: Bull. U. S. Geol. Survey No. 8, 1884, pp. 1–56.

instances of very large openings below the level of ground water are furnished by the caves in the lead and zinc district of Missouri. Here, in consequence of extensive pumping operations, the level of ground water has been lowered from a few meters to 45 to 60 meters. At various places below the level of ground water caves of considerable magnitude have been found, some nearly 60 meters in length and with rooms 12 to 15 meters in width. These caves are lined with crystals of calcite. The faces are perfectly clear. It is almost certain that the crystals continued to grow until the level of ground water passed below them. The caves are, in fact, like gigantic geodes with great scalenohedral crystals, some of them a half meter or more in length, projecting everywhere from the walls. No stalactites or stalagmites are found, or any of the other peculiar phenomena so characteristic of caves above the level of ground water in the belt of weathering. These caves, before transferred from the belt of cementation by the lowering of the level of ground water, were being filled, and had the process continued sufficiently long there would have been formed great masses of crystalline calcite analogous to the masses of that mineral which are sometimes elsewhere found.

Concluding from the geological facts observed, it seems perfectly clear to me that the fundamental fact of the part of the zone of fracture between the level of ground water and the zone of anamorphism is that cementation is the most characteristic process, and therefore the one which properly gives its name to the belt.

BOUNDARIES OF BELT OF CEMENTATION.

It has been explained (pp. 409–411) that in different areas the level of ground water is at different depths from the surface, varying from zero to 300 meters, and exceptionally to a thousand meters.

It has been shown that the level of the upper surface of the ground water is not horizontal, but undulating, and that the undulations of the level of ground water roughly follow the topography, as shown by the fact that upon many hills and mountains wells reach water of saturation at the very moderate depths of a few meters to 50 meters. A topographic map of a region is to a certain extent a map of the level of ground water, but the latter shows less accentuated contours. The elevation of the contour of the ground water at a given place is less than the elevation of the

surface contour by the depth of the level of ground water. It has also been seen (pp. 411–413) that the surface of ground water rises and falls from a few centimeters to a number of meters, and that therefore the upper boundary of the belt of cementation is somewhat variable.

The lower limit of the belt of cementation is the lowest horizon at which there may exist abundant openings in the rocks of supercapillary and capillary size. It has already been pointed out (pp. 190–191) that to this limit the rocks are self-supporting, but below it the rocks are not sufficiently strong to support themselves, so that if openings were supposed to be produced they would be closed by flow.[a] It has been calculated that for the strongest rocks the bottom of the belt of cementation may be as deep as 10,000 or possibly 12,000 meters, although for most rocks under ordinary conditions the bottom of the belt of cementation is believed not to be nearly so low. With the same kind of rock the bottom of the belt of cementation is at different depths under different conditions. For instance, when earth movements are rapid the belt might extend considerably deeper than when they are slow. The belt of cementation, extending as it does from the level of ground water to the bottom of the zone of fracture, is much broader than the belt of weathering.

CONDITION OF WATER IN BELT OF CEMENTATION.

The question whether hydrostatic pressure increases sufficiently fast with depth to prevent the water from passing into the form of gas needs to be answered. If the average temperature at the surface be assumed to be 0° C.—and in the arctic regions the average temperature is probably lower rather than higher than this—and if the increment of increase of temperature be taken as 1° C. for every 30 meters, the critical temperature of water, 365° C., is at a depth of 10,950 meters. If the average temperature at the surface were supposed to be 25° C., about the maximum for the tropical regions, in order to reach a temperature of 365°, the critical temperature of water, a depth of 10,200 meters would be required.

At any given place the water is subject to the pressure of the superincumbent column of water. Supposing the temperature of the water were 100° C., or just at the boiling point, at the surface of the earth (the most

[a] Van Hise, C. R., Principles of North American pre-Cambrian geology: Sixteenth Ann. Rept. U. S. Geol. Survey, pt. 1, 1896, pp. 591–594.

unfavorable assumption to holding the water as a liquid), the water would be a liquid in the belt of cementation, as is shown by the following table based upon this supposition, column (1) being temperatures, column (2) being pressures necessary to hold water as a liquid at these temperatures, column (3) being depth in meters at which the pressures would be produced, column (4) being the depth which would be required to produce the temperatures on the supposition that the increment of the increase of temperature is 1° C. for every 30 meters, and column (5) being the actual temperatures which exist upon this supposition at the depths represented by column (3).

Relations of pressures, temperatures, and depths in ground water.

(1) Temperatures.	(2) Pressures corresponding to temperature of column 1.	(3) Depth necessary to produce pressure of column 2.	(4) Depth necessary to produce temperature of column 1.	(5) Temperatures actually existing at pressures and depths of columns 2 and 3.
° C.	*Atmospheres.*	*Meters.*	*Meters.*	*° C.*
120	2.0	20	600	100.66
180	10.0	100	2,400	103.33
225	25.0	250	3,750	108.33
265	51.0	510	4,950	117.00
310	99.0	990	6,300	133.00
340	148.0	1,480	7,200	149.33
365	205.5	2,055	7,950	168.33

A fuller table, showing the relations of temperature and pressure between 225° and 365° C., at intervals of 5° C., is given below.[a]

Relations of temperatures and pressures of water.

Temperatures.	Pressure necessary to hold water as liquid.	Temperatures.	Pressure necessary to hold water as liquid.
° C.	*Atmospheres.*	° C.	*Atmospheres.*
225	25.1	300	86.2
230	27.5	305	92.2
235	30.0	310	99.0
240	32.8	315	106.1
245	35.5	320	113.7
250	39.2	325	121.6
255	42.9	330	130.0
260	46.8	335	138.8
265	50.8	340	147.7
270	55.0	345	157.5
275	59.4	350	167.5
280	64.3	355	178.2
285	69.2	360	188.9
290	74.5	365	200.5
295	80.0		

From these tables it is seen that the hydrostatic pressure at various depths is normally far in excess of that required to hold the water in the form of a liquid, or, looked at in another way, for any given depth the temperature is not sufficiently high to allow the water at that depth and pressure to exist in the form of a gas.

It therefore appears perfectly clear that where the increase in temperature with depth is normal the water remains as a liquid to its critical temperature, i. e., 365° C., and that the depth of the zone of water circulation is, therefore, about 10,000 or 11,000 meters. In another place (pp. 189–190), it has been shown that this approximates to the greatest depth at which continuous crevices and cracks can long exist in the earth. It therefore follows that in the belt of cementation the water is normally in the form of a liquid to the bottom of the zone. Where magma is intruded in the lithosphere the temperature may become so high that this statement will not hold. But this is the exceptional, not the usual case. Furthermore,

[a] Preston, Thomas, The theory of heat, Macmillan & Co., London, 1894, p. 385.

it is conceivable that as a result of deformation itself the temperature of the rocks may become so high as to convert the water present into the form of gas, but, from investigations upon metamorphism, it is believed to be probable that this condition of affairs rarely obtains, since, as shown on pages 690–692, long before the critical temperature of water is reached solution and deposition of rock material, or recrystallization, readily takes place, and in this change the work converted into heat is far less than in mechanical granulation.

In conclusion the general statement may be made that in the belt of cementation water is commonly in the form of liquid, and only exceptionally in the form of gas.

AMOUNT OF WATER IN BELT OF CEMENTATION.

It has already been suggested that the belt of cementation might be called the belt of saturation. This implies that the openings in the belt of cementation normally are filled with water solutions; therefore, the answer to the question as to the amount of openings in the belt of cementation approximately answers the question as to the amount of water there contained. It has been seen that in the belt of weathering the openings vary from a small amount to 40 or 50 per cent or more. In the belt of cementation the amount of pore space varies from zero to a maximum as high as 28.28 per cent, the actual amount of pore space found by Buckley in the Dunnville sandstone of Wisconsin.[a] The mechanical sediments, especially sandstones which have not been much cemented, contain very large amounts of pore space. The volcanic fragmental rocks also furnish considerable pore space. The very dense rocks, especially the plutonic igneous rocks, have a very small amount of pore space unless they have been fractured. Wherever the rocks have been deformed above the zone of anamorphism fractures of all classes are produced, including joints, faults, bedding partings, fissility, and brecciation fractures. The amounts of openings which are thus produced may vary from a fraction of a per cent to as large a per cent as in the porous sandstones, as, for instance, in breccias. But the openings which originally existed in the rocks or which have been produced by deformation are in all stages of cementation. Also

[a] Buckley, E. R., Building and ornamental stones of Wisconsin: Bull. Geol. and Nat. Hist. Survey Wisconsin No. 4, 1898, table v, p. 403.

in all probability the amount of pore space gradually decreases in passing from the upper to the lower part of the belt of cementation. All of the foregoing uncertain factors make any estimate of the water of the belt of cementation little better than a guess. On page 128, assuming there is

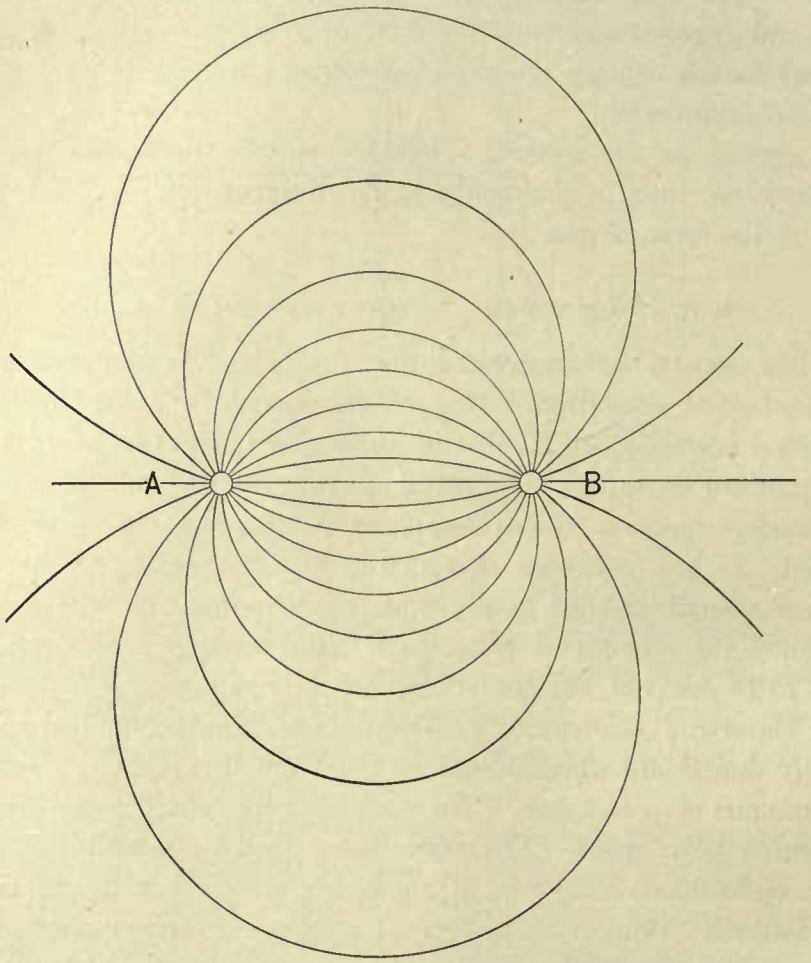


FIG. 7.—Ideal horizontal section of the flow of ground water through a homogeneous medium from one well to another.

present only one-fifth as much as Dana's estimate of 2.67 per cent by weight as the average amount of water in the upper part of the belt of cementation, supposing that from this amount it gradually decreases to zero at the bottom of the belt, and assuming the belt to extend to a depth of 10,000 meters, I have calculated that the amount of water in the belt, if concentrated in a stratum, would make a sheet 69 meters thick. How-

ever, it may be that this estimate is too small, and that the amount of water of the belt of cementation may be two or three times this amount.

CIRCULATION OF WATER IN BELT OF CEMENTATION.

VIGOR OF CIRCULATION.

The vigor of the circulation in the belt of cementation is best shown by the amount of work which has been accomplished in cementation of rocks

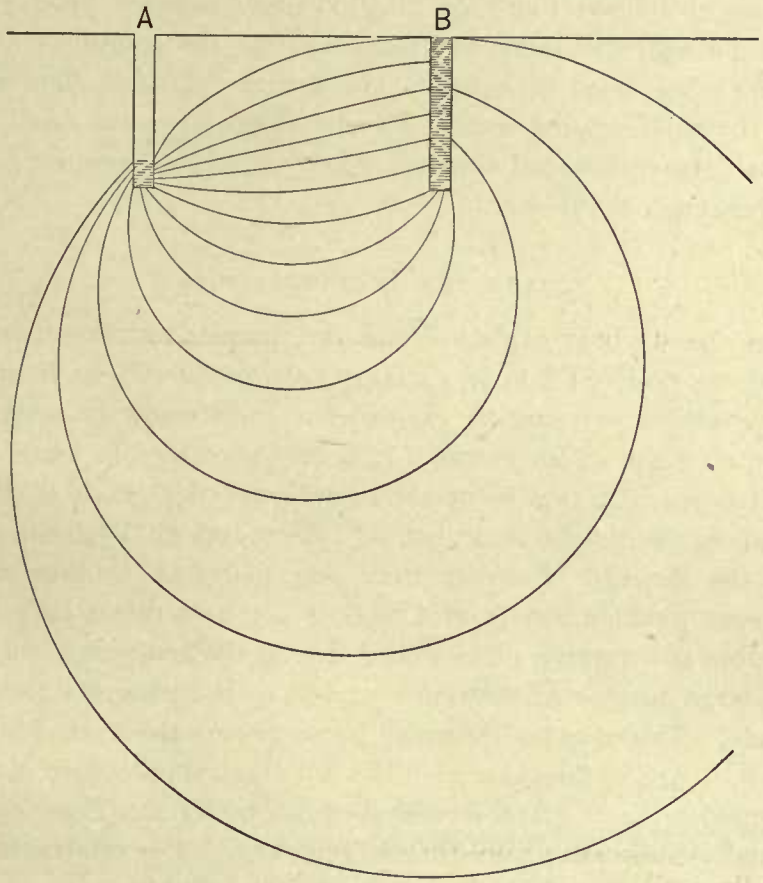


FIG. 8.—Ideal vertical section of the flow of ground water through a homogeneous medium from one well to another.

by ground waters. It is shown in another place that great sandstone formations, which must originally have had a pore space of from 32 to 40 per cent, have been completely cemented by the deposition of silica. (See pp. 865–868.) It is further shown that the amount of silica thus deposited is

enormous—to be measured in tens of thousands, and probably hundreds of thousands of cubic kilometers. The amount of silica which the waters of mineral springs carry is, on the average, less than 2 parts in 100,000. In only a few cases is the amount greater than 10 parts in 100,000, although in one case, that of San Bernardino spring of California, the amount runs as high as 22 parts in 100,000.[a] Supposing the amount of silica deposited by underground waters to be as high, on the average, as 1 part in 100,000 (and the amount deposited is invariably less than that in solution), it would be necessary to believe that over 260,000 times as much water must have circulated through the sandstone formations as the enormous amount of quartz which has been deposited. The amount of silica assumed to be deposited by underground waters may be too great or too small, but it is certain that many thousand times as much water as deposited quartz has circulated through the rocks.

CHARACTER OF CIRCULATION.

It has already been explained that the complex movements of ground water may be resolved into two components, horizontal or lateral movements and vertical movements. In order to understand the work done by underground water in its journey, it is first necessary to know the path which it follows. On this point the recent analytical work of Prof. C. S. Slichter gives the desired information.[b] According to Professor Slichter's analysis, the flowage of water from one place to another through a homogeneous medium, say from A to B, is not by a direct path, but by a large number of diverging paths from A during the first part of the journey, and by a large number of converging paths to B during the latter part of the journey. This may be illustrated by supposing the water to be poured into a well, A, and to flow to a well, B. The horizontal course of the water is represented by fig. 7, and the vertical course by fig. 8. These conclusions apply equally well to any porous rock, such as a soil or sandstone in which the spaces are distributed in a somewhat uniform manner.

It is apparent that Slichter's conclusions have far-reaching consequences as to the flowage of ground water. In the passage of the water from the

[a] Peale, A. C., Mineral springs of the United States: Bull. U. S. Geol. Survey No. 32, 1886, pp. 156, 187, 192, 195, 212, 213.

[b] Slichter, C. S., Theoretical investigation of the motion of ground waters: Nineteenth Ann. Rept. U. S. Geol. Survey, pt. 2, 1899, pp. 297–384.

top or slope of a hill to a point of issue at the foot of a hill, supposing these to be the only points of entrance or issuance of the water, and supposing the spaces to be uniform, the vertical course would be represented by the lines of fig. 9 and the horizontal course would be represented by the lines of fig. 7.

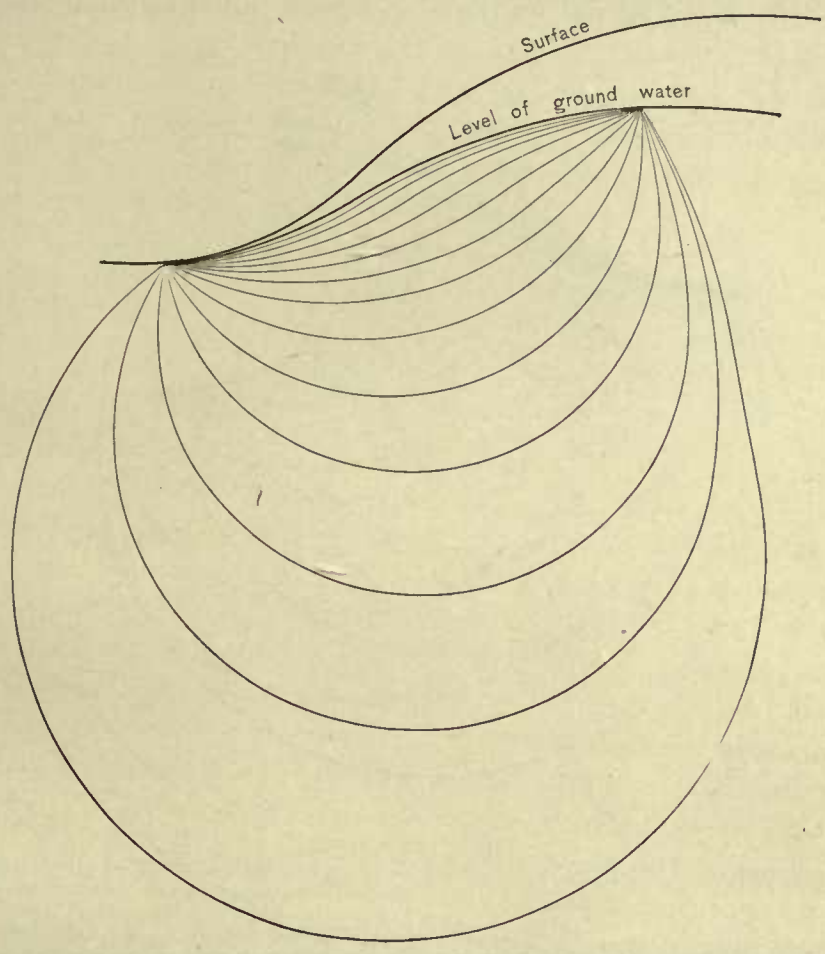


FIG. 9.—Ideal vertical section of the flow, through a homogeneous medium, of ground water entering at one point on a slope and issuing at a lower point.

In an actual case of ground-water flowage the water does not enter the ground at a single point, but at every point of a slope. As a simple case, we may suppose that the water entering on a slope reaches the surface again at the level of a stream in an adjacent valley. To get an idea of the complexity of the flow in this ideal case we may arbitrarily select a number of points where the water enters and trace out its course. We may plat by

different kinds of lines the vertical components of the flowage of the water which enters at each place independently of the water that enters at other places. (Fig. 10.) In the figure we have a series of intersecting lines representing the vertical components of movement.

It is not supposed that water actually follows paths similar to those represented by the figure, for there is mutual interference of the water

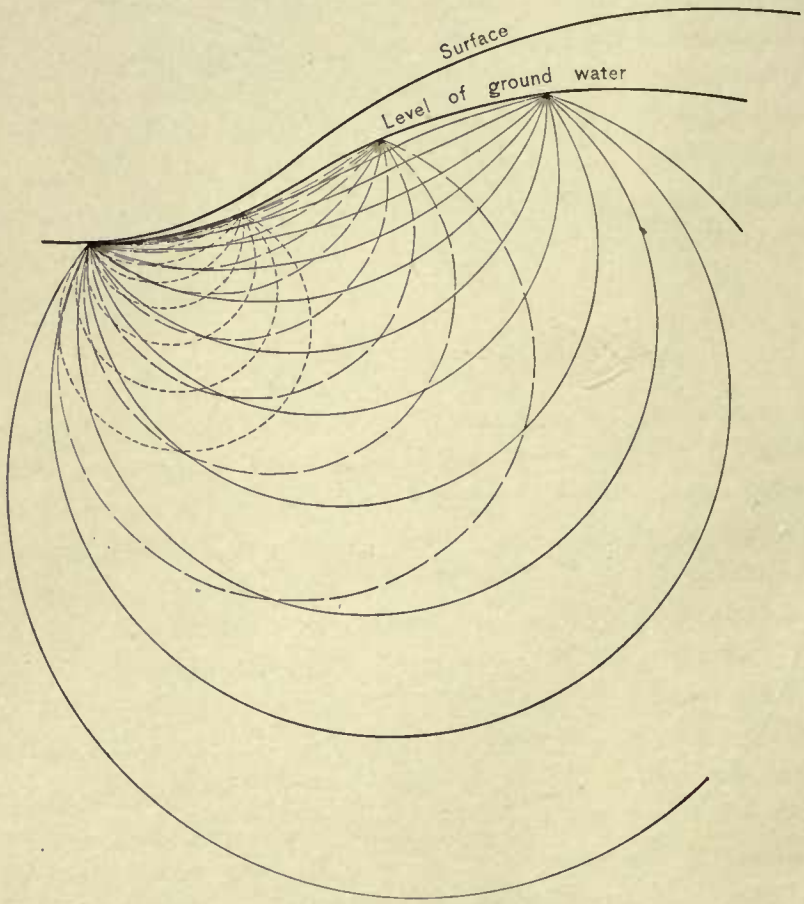


FIG. 10.—Ideal vertical section of the flow, through a homogeneous medium, of ground water entering at three points and issuing at a single point, each system of flow being independent of the others.

entering at the various points. As a result of this the water entering the opening nearest the exit would take a more direct course than the average of that platted; but, as a consequence of this, the water from the next opening up the slope would take a more indirect course, on the average, than that platted, and so on. The total result would be to give an average course for the water which may be represented by combining the inde-

pendent curves. (Fig. 11.) The effect, so far as the geological action of the underground water is concerned, would be approximately the same whether the course of the water were that represented by fig. 10 or that represented by fig. 11. This statement, applicable to a few points of entrance and one of exit, is equally applicable to a great number of points of entrance and one of exit. The statement can be further extended to

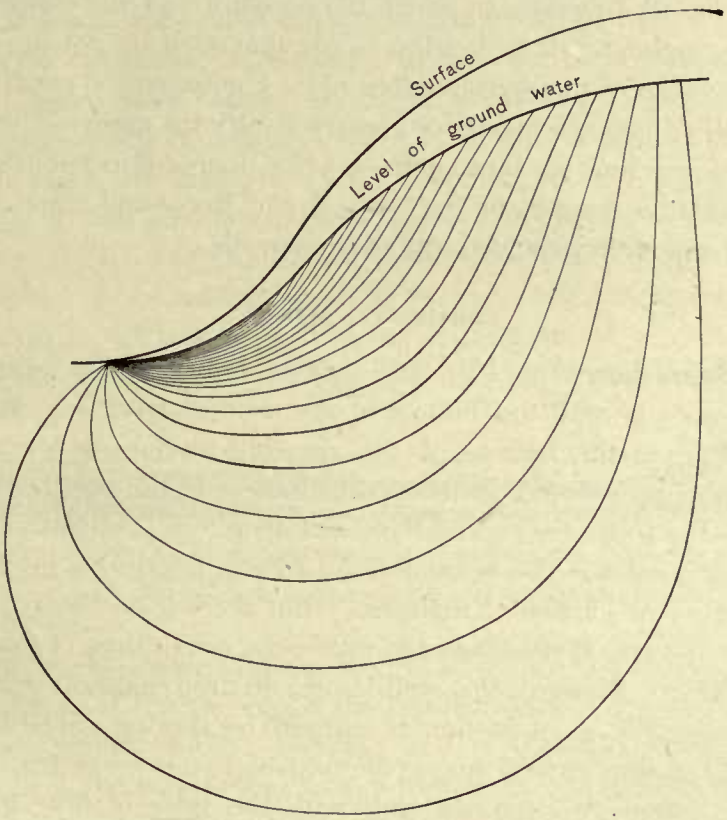


FIG. 11.—Ideal vertical section of the flow, through a homogeneous medium, of ground water entering at many points along a slope and issuing at a single point at a lower elevation.

an indefinitely great number of points of entrance distributed along the contours of the slope as well as up the slope and to many points of exit at or near the level of the valley.

Disregarding the lateral movement after the water reaches the level of ground water, the sea of ground water at a given place might be considered as a column moving downward as rapidly as the increment of ground water is added from above. However, the lateral movement which is super-

imposed upon the vertical movement carries it sooner or later to some point where upward movement is taking place. Thus the amount which continues downward is an ever-decreasing fraction of the amount of precipitation which joins the sea of ground water.

Thus far the discussion of the flowage of ground water has been carried on as if it were through a homogeneous porous medium extending indefinitely in all directions in which the pressure and the temperature are the same throughout. It is needless to say that such are not the conditions of natural systems of underground flowage. Under natural conditions there are many other factors which very greatly modify the nature of the flowage. Among these are limiting formations, gravity, increase in temperature with depth, the relative lengths of the vertical and horizontal components, and preferential use of large and continuous channels.

LIMITING FORMATIONS.

It has been shown (pp. 190–191) that the bottom of the belt of cementation corresponds with the bottom of the zone of fracture. It has been explained that to the bottom of the zone of fracture supercapillary or capillary openings may exist. Below the bottom of the zone of fracture the openings in the rocks are subcapillary and therefore practically impervious to a rapid circulation. The bottom of the zone of fracture is the lowest possible boundary of efficient circulation. But there is no theoretical reason why a ground-water system may not utilize the entire zone of fracture to its lower boundary. Indeed, the well-known hydrodynamical principle that the entire available cross section is utilized by flowing currents demands that the circulation extend to the bottom of the zone of fracture. This generalized statement conforms well with the lines of flow in a homogeneous medium as determined by Professor Slichter. (See figs. 7 and 9.) It therefore appears highly probable that, in any system of ground-water circulation, where there is no impervious rock nearer the surface than the bottom of the zone of fracture the entire zone of fracture is searched, although waters joining and departing from the underground sea disappear and appear at its surface. While this is true, other things being equal, the more direct route is utilized to a greater degree than the more indirect route, and therefore the remoter corners of available space have relatively

small circulations The principle of the distribution of the flowage of water over the entire available area is well illustrated by the case of water flowing horizontally into a beaker from one side and overflowing the beaker on the other side. The movement of the water is not confined to the liquid near the surface, but all portions of the water in the beaker, from the top to the very bottom, take part in the flowage, although, of course, the rate of movement is much more rapid at the top than at the bottom.[a]

While the circulation may extend to the very bottom of the zone of fracture, in many cases before that depth is reached a stratum is met all the openings of which are subcapillary. As shown on pages 143–146, such a stratum is practically impervious, and therefore becomes a practical limit of circulation in that direction. Such impervious strata may be only a few meters below the level of ground water, and thus the circulation be exceedingly shallow. From such a position an impervious stratum may be at various depths to the bottom of the zone of fracture.

While one system of circulation may thus be of very limited depth, it

FIG. 12.—Ideal section illustrating the chief requisite conditions of artesian wells. A, a porous stratum; B and C, impervious beds below and above A, acting as confining strata; F, the height of the water level in the porous bed A, or, in other words, the height of the reservoir or fountain head; D and E, flowing wells springing from the porous water-filled bed A. After Chamberlin.

does not follow that other systems of circulation are not utilizing the other parts of the zone of fracture below the first circulation; for very frequently a belt below, which contains openings and is available for flowage, may elsewhere reach the surface and have a feeding area. Indeed, such are the circulations of many systems which are limited above by impervious strata. One of the simplest of such systems is represented by fig. 12. There are an indefinite number of variations of the systems of underground circulations, dependent upon various combinations of pervious and impervious strata. In some instances there may be several superimposed or adjacent systems, the relations of which are exceedingly complex. Some of the cases are of general geological interest. A number have been discussed by

[a] Slichter, C. S., Theoretical investigation of the motion of ground waters: Nineteenth Ann. Rept. U. S. Geol. Survey, pt. 2, 1899, p. 331.

Chamberlin and others in connection with artesian waters;[a] but the best illustrations of complex systems have been worked out in connection with ore deposits, and in the chapter on that subject a number are discussed.

GRAVITY.

Thus far the full effect of gravity upon the character of the circulation has not appeared. The discussion has been carried on as if the movement of the ground water were controlled by simple pressure. But gravity is ever pulling the water downward. This force, in the early part of the journey, accords with the downward movement produced by head, and the result is that the water follows a deeper course than it would if moving through a homogeneous medium, in a manner similar to that of an electric current.

INCREASE OF TEMPERATURE WITH INCREASE OF DEPTH.

It has been repeatedly stated that the normal increase of temperature with increase of depth is 1° C. for each 30 meters. It has been pointed out (pp. 140–141) that the viscosity of water decreases as the temperature increases, and that the flowage of water is relatively rapid in proportion as it has low viscosity. Indeed, in capillary openings it has been shown (p. 139) that the flowage is inversely as the viscosity. When it is remembered that the pore spaces of the ordinary mechanical sediments are of capillary size, it is seen that this principle is very important in the flowage of ground water. At a depth of 1,350 meters, supposing the increment of temperature to be normal, the ground waters would have a temperature of 45° C. greater than at the surface. At a depth of 2,700 meters the ground waters would have a temperature of 90° C. greater than at the surface. The viscosity of water at 45° C. is only about one-third as much as at 0° C., and at 90° C. is only one-fifth as much as at 0° C. (See p. 141.) In the lower part of the zone of fracture the temperature of water varies between 100° C. and the critical temperature of water, 365° C. (See pp. 566–569.) If we suppose that at temperatures above 90° C. the viscosity decreases at

[a] Chamberlin, T. C., Artesian wells: Geol. of Wisconsin, 1873–79, vol. 1, 1883, pp. 690–691; also vol. 2, 1878, pp. 149–152. Leverett, Frank, The water resources of Illinois: Seventeenth Ann. Rept. U. S. Geol. Survey, pt. 2, 1896, pp. 802–803. Hill, R. T., Geography and geology of the Black and Grand prairies, Texas: Twenty-first Ann. Rept. U. S. Geol. Survey, pt. 7, 1901, pp. 398–401.

the same average rate as between 0° C. and 90° C., at a depth of 9,000 meters, where the temperature is probably about 300° C. greater than at the surface, the viscosity would be only about one-twentieth of that at the surface. From the foregoing it appears that in capillary openings in the part of the zone of fracture below 1,350 meters, with a given head, the flowage of water for capillary tubes of a definite size would vary from about three times to about twenty times faster than at the surface. These numbers are not accurate, because water at the surface usually has a higher temperature than 0° C., but the error is not so great but that the conclusion follows that increase of temperature with depth is a very important factor, tending to promote a circulation in the deeper parts of the zone of fracture, for water follows the lines of least resistance; therefore, ground water, on the average, follows a deeper path than it would were the temperature and viscosity uniform.

RELATIVE LENGTHS OF VERTICAL AND HORIZONTAL COMPONENTS.

The vertical component of the journey of ground waters in the belt of cementation may be considered as confined to the zone of fracture, and is probably measured by 10,000 meters, or at most by 12,000 meters. The lateral component, on the other hand, may vary from a few meters to hundreds or even a thousand or more kilometers. There can be little doubt that, on the average, the horizontal component is much greater than the vertical component. No limit can be assigned to the horizontal movement of water. It is known that the nearest source for artesian waters may be many kilometers from the wells. For instance, in the James River Valley, Dakota, the Dakota sandstone yields abundant water. The nearest place at which this sandstone outcrops is several hundred kilometers distant, and it therefore appears highly probable that the horizontal movement of the ground water is measured by hundreds of kilometers, while its vertical journey is probably less than 1,000 meters. Doubtless in this case the horizontal distance which the water has journeyed is far greater than the average, but still the average journey is probably one of considerable length.

The length of the horizontal component of the journey has much to do with the depth of the circulation. Where the horizontal component is

comparatively short, not many times longer than the vertical component, there is a strong tendency for the circulation to be relatively shallow. Where, however, the horizontal component is very great, the relatively short distance between the bottom and top of the zone of fracture of a porous stratum is of comparatively little consequence. In such cases the circulation through the deeper channels, provided they are equal in area and size to the shallow channels and the water is of the same temperature, might be practically the same as through the shallow ones. For instance, in the case already cited of the Dakota sandstone of the James River Valley, its thickness, about 100 meters, is insignificant compared with the horizontal journey of hundreds of kilometers. Therefore, in such a case, if the sandstone were equally porous throughout and of the same temperature, for the greater part of the journey there would be no appreciable difference between the amount of flow in the upper and that in the lower part of the sandstone, although in the very early and very late stages of the journey the upper part of the sandstone would have a greater flow. Where the horizontal journey is long, it is possible, on account of increase of temperature, giving decreased viscosity, that the circulation is more rapid through the lower part of a formation than through the upper part. This would almost certainly be true if all parts were equally porous. But if this were so, sooner or later the more rapid flowage would carry the process of cementation of the lower part of the formation farther than the higher part; and as the openings became partially closed, this would tend to lessen the amount of the deeper circulation.

PREFERENTIAL USE OF LARGE CHANNELS.

A very important factor in the flowage of ground water is the great variation, in any natural system of underground flow, of the area of available space and the rate of movement. In nature the points of entrance for ground water are indefinitely numerous, and the places of exit comparatively few. The water falls upon the ground everywhere and enters the innumerable pores. After a longer or shorter underground course, perhaps passing under many subordinate hills and valleys, it escapes to the surface as a spring or by seepage, nearer the drainage level than where it entered the ground. The water began its journey through an almost infinite number of openings; it issues at many openings, but these are few compared with the vast number of those at which it entered.

This conclusion is based on the following facts: Openings in rocks are never of uniform size. It has been seen that the resistance to flow in capillary openings is far greater than in supercapillary openings. In small supercapillary openings the resistance is greater per unit of flow than in larger ones. Thus there is a strong tendency for the water starting through innumerable small openings to converge into larger and larger openings, because these are the lines of least resistance. Of course, water may go long distances underground without finding larger openings than those near the surface, as in some sandstones; but if large openings exist, they are fully utilized. Finally, when a single opening or a group of openings larger than the average reach the surface at a lower altitude than the average level of entrance of the water, there is a spring.

This reasoning is confirmed by experimental work of King, who finds that the flow in the Amherst sandstone of Wisconsin is faster along than across the bedding planes. The openings along the bedding planes are larger than those between the grains. The first are largely utilized in flowage along bedding and the second must be utilized in flowage across bedding planes.[a]

From his experimental work King holds "that the movements of ground water across long distances must take place in considerable measure through passageways larger than those which depend upon the pore space fixed by the diameters of the grains which constitute the beds themselves."[b]

While I believe that in proportion as openings are large they are much more fully utilized than a similar area of distributed openings of small size, we must remember that the movement of the widely dispersed deep water is often excessively slow, and that under these circumstances the resistance in the capillary tubes per unit distance is reduced to a very small, almost an infinitesimal, amount. (See pp. 141–142.) Therefore capillary openings between the grains in the cases of great sandstone and similar formations may be the chief channels of circulation for large quantities of water and for long distances. That such openings are the chief channels through which the water actually flows in the deeply buried sandstones bearing artesian waters is indicated by the fact brought out by

[a] King, F. H., Principles and conditions of the movement of ground water: Nineteenth Ann. Rept. U. S. Geol. Survey, pt. 2, 1899, p. 126.

[b] King, cit., p. 249.

Slichter, that the pressure a short distance from the bottom of a well is commonly as great while the well is flowing as it is at the mouth of the well when the flow is stopped.[a] If the flowage was mainly, or even largely, through supercapillary openings, this would not be the case.

Large openings are favorable to a somewhat direct course; small openings are favorable to a circuitous route. As the openings decrease in size, a more circuitous route must be taken, for to pass a given volume of water from one point to another it is necessary that a wide range of openings be utilized. It has been pointed out (pp. 569–570) that the openings of the belt of cementation are relatively large in its upper part and probably diminish in magnitude as depth increases. So far as this is true, therefore, large channels for trunk circulation are, on the average, most numerous near the level of ground water, and diminish in number and size as depth increases. From this, and the principle that the ground water tends to utilize the larger openings to the greatest extent, it follows that the abundant circulation tends to follow a relatively shallow course.

The direct course of water in large openings is illustrated by limestone regions where there are numerous large joints and sometimes caves within which the water is quickly concentrated. In such instances the flowage of water is very largely in the upper part of the zone of fracture.

RESULTANT CIRCULATION.

Summarizing, it has been seen that the movement of water in a homogeneous medium is similar to the movement of a current of electricity through a homogeneous medium, in that it utilizes the entire available cross section. But by the water the more direct course is utilized to a much greater extent than the less direct course. For the actual underground circulation this general statement must be modified in various ways. The circulation is limited wherever a formation is met in which the openings are subcapillary. Gravity and increase of temperature with depth tend to cause the water to take a deeper course than it otherwise would. On the other hand, the preference of water for the larger openings, and the greater abundance of openings of large size near the surface, tend to give the water a shallow course. Therefore the influence of gravity and temperature and that of large openings oppose each other. Which of these two opposing

[a] Slichter, C. S., Theoretical investigation of the motion of ground waters: Nineteenth Ann. Rept. U. S. Geol. Survey, pt. 2, 1899, pp. 363–364.

factors is the more important is uncertain, but probably the existence of larger fractures near the surface is more important than the effect of gravity and temperature.

It has been seen that during the first part of the underground journey of water the vertical component is downward, and that during the latter part of its journey the vertical component of much of it is upward. It follows that, on the average, the downward movements of water are through the smaller, and the upward movements through the larger, openings in the rocks. Of course, where large openings are available for the downward-moving water they are fully utilized, and therefore to a greater extent than a similar area of smaller openings. But even if this be true, the statement still holds that, on the average, the larger openings are more extensively used by the upward-moving water than by the downward-moving water. From the foregoing it appears that a system of circulation of ground water has a very close analogy to a tree of peculiar character.

The points of entrance of water are the ends of the indefinite number of twigs; these twigs unite into a branch; the branches unite to produce a larger branch; the larger branches unite into a trunk; and at the end of a trunk is a spring. The analogy of an underground drainage system to a tree is even closer than that of a surface system; for in a system of underground water circulation three dimensions are concerned to an important extent, while in a surface system of drainage the movement of the water is approximately confined to a plane. But, from what has gone before, it is clear that the tree of ground water has a peculiar shape. The twigs and branches have an important downward component; the larger branches of the tree may be considered as approximately horizontal; and the trunk usually has an upward component, which may be slight but is often important. Thus twigs, branches, and trunks together ordinarily make a great U. Where the water issues near the places of entrance the sides of the U are rather close together. Where there is great lateral movement of the water the sides of the U are very far apart. Such a system of ground water is somewhat similar to that of a surface system of drainage.

Ordinarily where the water first enters the underground sea the area of available space is exceedingly great and the rate of movement is very slow. As the water gathers in the larger openings the speed increases, and in the final trunk channels the water may have a very rapid movement, as

shown by springs. These facts are important in connection with the variation in the size of the openings. The earlier movements are in the capillary openings, where the resistance to rapid flow would be great; but here the movement is slow, and consequently the friction is very small. (See p. 581.) As the water passes into the supercapillary branch and trunk channels, the important factor in friction is not that between the moving water and the adherent films, but the internal friction. The total friction in these larger channels is almost indefinitely small as compared with the friction of the same amount of water moving at the same rate through the same area subdivided among capillary openings; for the area of contact, and therefore the friction between the moving liquid and that fixed to the walls, is inversely as the size of the openings. (See pp. 136–137.)

An underground circulating system is ideally illustrated in many arid and semiarid regions. In the United States it is especially well illustrated in the Great Basin and in southern California. In these regions the early parts of the courses of many streams are in mountain gorges, where usually considerable streams are above ground. As the streams leave the gorges and pass out to the plains their courses are over their own deposits, consisting of great alluvial fans of material, coarse and fine, which is called "wash." The streams at these places commonly pass underground, and there, as shown by drilling for water, follow somewhat definite channels. Lower in the course of the drainage systems a large part of the underground water frequently issues in a series of springs or by seepage on a large scale, and continues its course above ground. The gravel and coarse sands furnish a close approximation to a homogeneous medium and ideally illustrate the laws of flowage given on pages 129–152, 572–576. Such an underground circulation as the above differs from an overground system in that the boundaries of the water courses are indefinite, in that the movement as compared with the movement overground is exceedingly slow, and in that the underground cross sections are necessarily much larger. The work of Professor Slichter shows that the ground water of the Arkansas River flows in gravels at a rate not greater than 3 to 5 meters a day.[a] Supposing the rate of movement of the overground streams to be 10 kilometers an hour, or 240 kilometers a day, and supposing the rate in the underground streams in the Great Basin or

[a] Slichter, C. S., The motions of underground waters: Water-Sup. and Irr. Paper No. 67, U. S. Geol. Survey, 1902, p. 43.

in southern California to be four times as great as the most rapid rate in the Arkansas sands—that is, 20 meters a day—the overground rate would be 12,000 times as fast as the underground rate. When it is remembered that underground about three-fourths of the space is occupied by sand and gravel, and that the openings present are more or less irregular, at the maximum the available openings are not more than one-fourth the entire space. It follows that, in order to accommodate the underground water, the channel would have to be 48,000 times larger than at the surface. This number may be an overestimate, but certainly an underground channel through sand and gravel to accommodate a certain amount of water must be many thousand times larger than an overground channel with the same slopes which accommodates the same amount of water.

While many streams in the semiarid and arid regions normally have an underground course as above described, at occasional times of flood, which may be for a brief season each year or may occur only once in a number of seasons, the mountain streams are of such increased volume that the underground circulation is not sufficient to dispose of the water, in which case there is for a time also an overground circulation, which usually follows approximately the same general course as the ground waters. It is at these times of flood that the fans of the wash are built up and the overground channels determined. Such circulations are ideally illustrated by the Santa Ana, San Gabriel, San Antonio, and other streams of southern California.

Excellent illustrations of underground flowage are furnished by artesian systems. For instance, in Wisconsin the Potsdam sandstone is an artesian water-bearing stratum. This sandstone is 200 to 250 meters thick. The annual precipitation in the district of its outcrop is approximately 50 centimeters. Supposing that one-half the rainfall enters the sea of ground water in the sandstone, this would give an additional increment every year of 25 centimeters. If the pore space of the sandstone be supposed to be $16\frac{2}{3}$ per cent, in order that the increment added shall find space in the sandstone without raising the water level it is necessary to suppose that the water of the previous year shall have moved downward 150 centimeters. In other words, the vertical flowage per annum is only 150 centimeters, or $1\frac{1}{2}$ meters. Suppose the dip of the sandstone to be 2 meters per kilometer; it would follow that the lateral movement of the

water, in order that the new water shall have room to enter the sandstone without raising the water level, should be three-fourths of 1 kilometer per annum. If the dip of the artesian-bearing strata were steeper the lateral movement would be much less. The above case, however, is approximately that of the Potsdam sandstone of Wisconsin. Since the average lateral movement of the water can not be supposed to be more than three-fourths of 1 kilometer per annum, the water which enters the artesian circulation at a distance of 150 kilometers from Chicago should, on the average, issue from the wells at Chicago 200 years after it enters the sea of ground water in Wisconsin.

In so far as the openings in the porous stratum are not of uniform size, the movement will be more rapid through the larger openings, and so far as this takes place the water rising in the artesian wells would remain underground for a less time than calculated; but, on the other hand, the remainder of the water which did not follow the larger openings would travel at a slower rate than calculated, and thus remain underground a longer time; and thus, so far as difference in porosity is concerned, the average would be as calculated.

The average length of time during which the water remains in the ground would probably be longer, perhaps much longer, than calculated, for all the premises are made so as to give the minimum time. For instance, the calculation is made upon the supposition that the porous stratum is homogenous and that there is no leakage through the overlying impervious structure, whereas it is certain that there is leakage. In so far as there is leakage the lateral movement would be slower and the calculated length of time should be increased.

Also the annual rainfall which enters the sea of ground water in the belt of cementation is not so great as 25 centimeters, for a considerable portion of the water which goes underground is evaporated from the belt of weathering. In so far as the amount is overestimated the length of time calculated—two hundred years—should be increased.

The above result as to length of time which water remains underground in an artesian circulation is not so surprising when we compare it with the exceedingly slow flow already mentioned for the underground water in the sands of the Arkansas River and of the alluvial cones of southern California, in which the descent of the level of ground water is many times

greater per kilometer than the gradient for the artesian water, as figured by dividing the difference between the head and the point to which the water would rise by the horizontal distance. Where the sandstone is perforated by artesian wells near Lake Michigan the water rises with a pressure which is a large fraction of the pressure due to head.

If, for instance, the city of Chicago be taken, the nearest point at which the Potsdam sandstone outcrops is about 150 kilometers, and the water for the Chicago wells is probably mainly derived from points 150 to 250 kilometers from Chicago. The average elevation of the catchment area above Chicago is 80 meters. The water of the early artesian wells at Chicago, before they were so numerous as mutually to interfere when allowed to flow, rose to an altitude of about 30 meters above the surface;[a] or, there is a loss, in the entire distance of 150 kilometers or more, of only about 50 meters of pressure. This small loss of head, which may be attributed to friction between the water and the sandstone, and within the water, is to be distributed through this entire distance. It follows that in the capillary openings of this sandstone the friction of the water is almost zero, else the pressure at the wells would not so nearly equal the pressure due to head. Of course the moment the wells are allowed to flow, and especially if there be a number of contiguous wells which are allowed to flow, the pressure rapidly drops. This is not due to friction through the major course of the water, where the movement is slow, but is due to friction adjacent to the wells, where the water is moving rapidly toward them. This is shown by the fact that at a distance of from 100 to 200 meters from a well the pressure is commonly as great while the well is flowing as it is at the mouth of the well when the flow is stopped.[b] Indicating the same thing is the fact that the flow of a well may be greatly increased by shattering the rock at the bottom of the well, thus producing supercapillary openings into which the water may issue from the capillary openings. If the area of these supercapillary openings be many times that of the cross section of the well, the chief source of friction is that of moving water in the well itself; for the water has a chance to slowly ooze from the capillary into the supercapillary tubes without rapid motion, and to make its way to the well tube through

[a] Leverett, Frank, The water resources of Illinois: Seventeenth Ann. Rept. U. S. Geol. Survey, pt. 2, 1896, pp. 805–806, 811.

[b] Slichter, C. S., Theoretical investigation of the motion of ground waters: Nineteenth Ann. Rept. U. S. Geol. Survey, pt. 2, 1899, pp. 363–364.

many supercapillary channels of much greater cross section than the well. The rapid movement is restricted to the section of water in the well, and there the friction is great. This Wisconsin illustration is typical of natural systems of ground water flow; for, as shown on page 583, a natural system of flowage simulates a tree. At the outset there are an indefinite number of minute openings through which the water slowly moves to the branch openings. In the branch openings the movement is faster. The branches unite into the trunk channels, and in these the movement of the water is rapid.

The analogy to a tree has been suggested in order to get definitely in mind the general character of the circulation of ground water. But the analogy must not be pushed too far. A tree commonly has but a single, continuous, solid trunk, although willows and other trees have many trunks. Very frequently, indeed commonly, the trunk channels of ground water circulation are very complex. While a main watercourse may exceptionally occupy a single open passage, ordinarily it occupies a number of interlocking passages. These may be the parallel openings of a complex fault, the smaller numerous openings of a zone of fissility, or the more open places of sandstones or conglomerates. In short, a trunk channel of ground water differs from other channels only in that because the openings are larger than the average, they are places where there is more circulation.

Thus far the discussion has not taken into account the geological work of the circulation itself. But the character of the circulation is being continually affected by the material deposited.

Later in this chapter it will be explained that under quiescent conditions the process of deposition of mineral material in the openings of the belt of cementation continues until the openings are practically closed. In proportion as this process is advanced the openings become smaller and the circulation slower. In many great, almost perfectly cemented formations, as the process neared completion, the movement of the ground water must have become exceedingly slow, and finally practically ceased. After a formation has been once cemented, orogenic movements may again produce fractures within it, and thus form new openings through which an underground circulation may again be set up.

GENERAL STATEMENT.

In conclusion of this part of the subject, while the lessened viscosity with depth, slow movement, and long journey are all very favorable to a deep circulation, I have little doubt that in porous strata large openings near the surface and the more direct course of a shallow journey result, on the average, in much larger flowage in the upper part of the belt of cementation than in the lower part.

TEMPERATURE OF ENTERING AND ISSUING WATER, AND TRANSFER OF HEAT.

Before taking up the work of ground water in the belt of cementation it is necessary to consider the relative temperatures of the water which enters and departs from the sea of underground water. Is the water which joins the belt of cementation colder or warmer than that which issues from it?

At a certain definite distance below the surface, in most regions from 12 to 15 meters, seasonal variations in temperature are eliminated; the thermometer discloses no difference between the temperature of winter and that of summer. The thermal conductivity of the rocks is so low and the amount of water which passes to the belt of cementation is relatively so small that the great variations of temperature of the atmosphere, of the rocks at the surface, and of the meteoric water, emphasized on pages 433–444, 458–460, at the depth of a few meters all merge into a temperature uniform for a given locality, but of course variable in different localities, and especially with latitude.

When the rain falls upon the soil it may be warmer or colder than the surface of the earth, but the part that sinks into the soil is subdivided between the pores of the rocks and comes into most intimate contact with them, so that when the water at the surface is warmer than the rocks it is cooled; when colder than the rocks it is warmed. Thus the two quickly assume nearly the same temperature. Doubtless downward-moving water is one of the most important of the agents which determine the fixed average annual temperature of the rocks a short distance below the surface. The reason for this belief is the high specific heat of water as compared with rocks. However, the relative influence of the heat given by water and that due to other climatic factors, such as latitude, altitude, etc., need

not here be discussed. For the present purpose the important point is that for any locality at a very moderate distance below the surface the water and the rocks have a common and practically invariable temperature.

It is highly probable that the point at which there is no appreciable annual change of temperature is not deeper, on the average, than the level of ground water. If this be so we may consider the ground water as entering the belt of saturation at a fixed temperature. Assuming this, in order to answer the question whether the water is colder or warmer when it issues from the belt of cementation than when it entered the belt, it is necessary to consider in what manner the water may gain or lose heat during the interval.

For the following reasons it appears highly probable that, on the average, the water gains heat during its underground journey:

(1) Earth movements are general for the lithosphere, and in many regions these are of the most intense character. So far as earth movements take place, to a very large extent the energy of the mechanical action finally passes into heat. Where the movements are forceful the amount of heat thus produced is considerable. The circulating underground water in contact with the rocks necessarily absorbs some of this heat.

(2) It has been shown that the dominant chemical reactions that take place in the belt of cementation are those which liberate heat. Of all the reactions characteristic of the belt of cementation it has been pointed out that hydration is the most important, and this process liberates a large amount of heat. The chemical reactions therefore furnish heat which the percolating waters must certainly absorb, in part at least.

In the lower zone, that of anamorphism (see p. 167), it has been pointed out that the dominant chemical reactions take place with absorption of heat. But where these reactions take place it is only through the expenditure of mechanical energy which liberates heat to a greater extent than that absorbed by the chemical reactions. That is, as a result of mechanical action and chemical action together, as fully developed on pages 110–113, there is a residuum of heat liberated to be absorbed by the water, and therefore if the reactions of the zone of anamorphism affect the temperature of the water of the belt of cementation at all it must be by addition of heat.

(3) Very large quantities of heat are brought into the belt of cementation by intrusive igneous rocks. The intruded rocks are partly cooled by

the transmission of their heat to the surrounding rocks and by conduction to the surface, but the underground circulating water in contact with the igneous rocks and in contact with the other rocks heated by them absorbs a large amount of the heat, probably a much larger amount than that transmitted to the surface through conductivity.

(4) After the water joins the sea of ground water its vertical component is at first downward. Because of the normal increment of increase of temperature—1° C. in 30 meters—the descending water gradually absorbs heat from the rocks. During the ascent the water tends to give heat to the rocks, because it is passing from rocks of higher to those of lower temperature. But the upward movement of the water is of shorter duration, is in larger openings, and is more rapid than its downward movement (see pp. 582–584); therefore it seems probable that in consequence of normal increase of temperature due to depth, more heat is transmitted to the water than is abstracted from it.

When we combine all four of these factors it follows to a certainty that the water in its journey absorbs heat, on the average, and therefore issues from the belt of cementation at a higher temperature than it enters it. Hence it appears perfectly clear to me, from general reasoning, that during the circulation of ground water it abstracts heat from the rocks.

So far as I know, no attempt has been made to prove this general statement by observation; but it appears to be highly probable that it could be proved by careful experiments. At the crests of elevations in various regions temperatures should be taken at the level of ground water. In the same regions the average temperature of the water issuing from springs should be observed. The two sets of data should be compared. While no general observations have been made along these lines, in some regions of recent orogenic movements and volcanism observation does clearly show that the temperature of the issuing water is higher than that of the entering water. This is well illustrated by the Cordilleran region of western United States. This is a region of comparatively recent epeirogenic and orogenic movements and of volcanism. Gilbert and others[a] have shown that, scattered throughout this vast region, occupying nearly one-third of the

[a] Gilbert, G. K., Volcanic rocks and mountains, with localities of thermal springs in the United States: U. S. Geog. Surv. W. 100th Mer., vol. 3, 1875, pp. 145–155. Howell, E. E.. Thermal springs: ibid., pp. 256–257. Stevenson, J. J., Mineral springs: ibid., pp. 478–487.

United States, are many springs the temperatures of which vary from 30° to 100° C. For instance, in the Yellowstone Park are a great number of hot springs and geysers, the temperatures of which approximate 100° C. That a vast amount of heat is brought to the surface by the underground circulation of this district can not be doubted. The number of springs in the Cordilleran region which are known as hot is very small as compared with those which are simply warm. The warm springs, according to Gilbert,[a] may be considered as those having a temperature between 18.3° and 37.7° C. (65° and 100° F.) or practically blood heat According to Gilbert,[b] the water of all the foregoing springs exceeds the mean annual temperature of the air by 8.3° C. (15° F.).

Although we have no data by which to verify the statement, I have no doubt whatever that the number of springs the temperature of which is slightly but measurably above the mean annual temperature exceeds many times the total number of all springs the temperatures of which are so notably above the normal temperature of the region as to be called warm or hot. Finally, it is highly probable that the amount of water which escapes through notable springs is small as compared with that which reaches the drainage of the valleys through small openings and seepage. The movement of this water is relatively slow, and it may be presumed that it is at but a slightly higher temperature at the point of issue than the average temperature of the rocks of the surface. But it is to be remembered that a slightly higher temperature of issuing water over that of the entering water through the vast number of springs of very moderate temperature, and through seepage, is probably of far greater quantitative importance than the marked increase of temperature in the comparatively few warm and hot springs. This illustrates the old principle that widespread small forces and agents may be of more importance, sometimes incomparably more, than the more conspicuous but more circumscribed forces and agents.

In other regions of recent orogenic movements and volcanism essentially the same facts prevail as in the Cordilleran region of America; and therefore observation, so far as it has gone, confirms the general reasoning given on pages 590–591, that water issues from the belt of cementation at a higher temperature than it enters it.

Aside from the matter of metamorphism, this conclusion has a bearing upon the refrigeration of the earth. The heat of the earth produced by

[a] Gilbert, cit., p. 148 [b] Gilbert, cit., p. 149.

mechanical action, produced by chemical action, transferred to within the zone of fracture by volcanism, and derived from the interior by conduction, so far as it escapes is largely transferred by means of water. If this conclusion be true the question immediately arises as to the effect upon the temperature gradient.

Barus states that, because of the chemical action of water in the pores of rocks, heat is liberated; and that we may consider the zone of circulation as a furnace. From this he concludes that the temperature gradient observed is probably not high enough, on the average, or the "observed rate of increase of temperature with depth is too large."[a] The reasoning applied to heat developed by chemical reactions would apply to that produced by mechanical action in the zone of fracture and to that introduced by volcanism. But in Barus's statement the fact that the water is in circulation is altogether neglected. This makes the case much more complicated than Barus supposed. The water is in circulation, and, as already shown, is constantly abstracting heat from the earth. Therefore it appears that, aside from volcanism, from the zone of fracture heat is being transferred to the surface in two ways—by conduction and by the convectional circulation of water. I suspect that the heat convectionally transferred by circulating waters is as great as or greater than that lost by conduction. The amount thus transferred by convection may more than compensate for that developed within the zone of fracture by mechanical and chemical action and by volcanism.

The above suggestions are offered to show that the problem of the heat gradient is much more intricate than has been supposed, and that the heat problem of the earth can not be treated as a simple one in which conduction is the only factor to be handled. The problem is so complicated by chemical action, by mechanical action, by igneous intrusions and extrusions, and by the water circulation in the zone of observation, that any conclusion as to the loss of heat of the earth and the depth to which cooling extends which ignores these disturbing factors is of very little value, to say the least.

[a] Barus, Carl, The compressibility of liquids: Bull. U. S. Geol. Survey No. 92, 1892, pp. 83–84.

VARIABLE MATERIALS AND CONDITIONS OF BELT OF CEMENTATION.

Within the belt of cementation the materials and conditions are variable, but not nearly so variable as in the belt of weathering. The materials within the belt of cementation include all the classes which exist in the belt of weathering (see pp. 429–430); that is, igneous rocks, sedimentary rocks, surficial rocks, metamorphosed rocks, and their variations and gradations; but ordinarily the alteration products are not nearly so complex in the belt of cementation as in the belt of weathering, and therefore the alteration forms of the belt are much less varied than those of the belt of weathering.

Water solutions are the main active agents at work in the belt of cementation. Gaseous solutions and organic compounds, which are so important within the belt of weathering, play a comparatively small part. The water solutions may contain any of the bases and acids which occur in the belt of weathering. (See pp. 457–458.) They may also contain gases in solution, of which oxygen and carbon dioxide are the more important, but others are of considerable consequence. In the belt of cementation the temperature varies with depth and also varies greatly in consequence of mechanical action and igneous intrusions. A great range of temperature is much more common than in the belt of weathering, but the speed of change at any place is slow, so that for a long time at any one place the temperature is relatively constant. The work of the belt of cementation is accomplished by mechanical and chemical agents, precisely as in the belt of weathering, but the character of the work performed is very different from that of the belt of weathering.

WORK IN BELT OF CEMENTATION.

The rocks in the belt of cementation are modified by mechanical work, by chemical work, and by igneous work.

MECHANICAL WORK.

The mechanical work of the belt of cementation occurs in connection with deformation. The mechanical work of wind, water, and ice, of changes in temperature, of plants and animals, so important in the belt of weathering, plays no part. The chief force producing deformation is gravity

acting directly or indirectly through orogenic movements and intrusives. The direct pressure due to gravity increases with depth. It is therefore increasing at areas where loading is taking place by sedimentation or igneous accumulations, and is decreasing in areas where denudation is going on. Heat is also a force producing mechanical effects. As a result of denudation, by which process the rocks approach nearer the surface; by sedimentation, by which process rocks pass deeper below the surface; by mechanical and chemical action, and by the intrusion of igneous rocks, the temperature is changed. Increase of temperature expands the material affected, and therefore induces compressive strains and tends to decrease the openings within the rocks. Decrease of temperature produces the opposite effect.

The mechanical work of deformation includes the processes of consolidation, strain within the elastic limit, and strain beyond the elastic limit. Each of these processes is considered in turn.

CONSOLIDATION.

Mechanical consolidation is a process by which the separated parts of a rock are brought closer together through pressure. The pressure may be due to the weight of the superincumbent rocks, to the lateral thrust of orogenic movements, to the hydrostatic pressure of igneous rocks, and to mineral growth during cementation and metasomatism. The very idea of the zone of fracture, to which the belt of cementation belongs, implies that the rocks and mineral particles are sufficiently strong to be self-sustaining.

In proportion as the rocks show openings, and especially in proportion as they are incoherent, mechanical consolidation is likely to produce an important effect. The incoherent rocks comprise the mechanical sediments and tuffs in their original condition. The coherent rocks comprise both of the above classes which have been more or less cemented and the massive rocks which may have openings due to various causes.

For the present purposes the mechanical sediments are of two general classes, the silts and muds, and the coarse sands and grits. The first of these classes is the one which is most affected by mechanical consolidation. In many cases the mineral particles of the fine-grained silts and muds appear to be separated by water. In such a rock pressure gradually squeezes out this water, bringing the mineral particles into contact. At the same

time the mineral particles are mechanically readjusted in reference to one another. In consequence of the two the volume of the material may be considerably decreased. The process of consolidation may continue until finally the particles are brought so close together that they cohere. As explained by Becker,[a] when the films of water between the particles become very thin, they may become an important factor in the coherence of the rocks. The molecular attraction of the water films and the adjacent particles, or their adhesion, and the cohesion of the molecules of the films may be sufficient to give the rocks a certain amount of strength. As the process of squeezing out the water goes on, many of the particles are brought so close together as to be within the sphere of molecular attraction independently of the separating films of water. So far as this is true the particles are welded by the pressure. The welding and the adherent influence of the water films may give the muds and silts marked coherence.

During the process of consolidation, as the water escapes the pressure to which it is subject gradually becomes less. Therefore if saturated or nearly so, during its escape it may deposit a portion of the material in solution, and hence cementation dependent upon mechanical consolidation may promote induration.

In proportion as the particles of the mechanical sediments become large and clean the process of mechanical consolidation becomes less important, for the points of contact rapidly decrease in number as the sediments become coarse, and where they are very coarse such contacts are so few that the rocks gain little strength as a result of close contact and the adherent effect of the films of water. Moreover, as shown by Professor Slichter,[b] coarse mechanical sediments deposited by water are usually arranged in a somewhat compact manner. This natural arrangement, while not the most compact possible, is so compact that experiments show that subsequent mechanical disturbances sufficient to displace the grains in reference to one another ordinarily result in decreasing the compactness of the packing, and therefore in increasing the volume of the rocks.

The tuffs are somewhat intermediate in character between the coarse and the fine mechanical sediments. They ordinarily include both classes

[a] Becker, Geo. F., The torsional theory of joints: Trans. Am. Inst. Min. Eng., vol. 24, 1895, p. 131.

[b] Slichter, C. S., Theoretical investigation of the motion of ground waters: Nineteenth Ann. Rept. U. S. Geol. Survey, pt. 2, 1899, p. 305.

of material in the same rocks. If originally arranged under air, they have a very much less compact arrangement than they or the ordinary sediments do if arranged under water. Thus many tuffs are in a condition in which mechanical adjustment of the particles by pressure may give a considerably more compact arrangement. Also, since between the coarse particles there are many fine particles, the number of points of contact between the particles may be sufficient to give considerable coherence by welding, and the strength is further increased by the adherent power of the water films, precisely as in the case of the muds and silts. Therefore it is probable that to a considerable extent tuffs may be consolidated by pressure.

In general in the zone of fracture the coherent rocks are sufficiently strong to support themselves, and mechanical consolidation is relatively unimportant. However, the openings produced by rather rapid movements may be subsequently gradually closed by the steady pressure of gravity or thrust. In the massive rocks containing no openings mechanical consolidation has no appreciable effect.

STRAIN WITHIN ELASTIC LIMIT.

All substances subjected to stress are more or less strained, and the amount of the strain is proportional, although not directly proportional to the stress. The rocks throughout the belt of cementation are all subjected to stress, and therefore to strain; for none are free from the weight of the superincumbent material, and in general they are subjected to compressive or tensile stresses parallel to the surface of the earth. It has been seen that in the belt of cementation the direct stress of gravity, and its indirect effect through orogenic movements, is sufficient to mechanically consolidate the rocks and to fracture them in the most extensive manner. It is clear that in a given case of rupture, before fracture took place the rocks must have been strained to the elastic limit. Therefore the amount of the strain within the belt of cementation varies from an insignificant quantity to strain to the elastic limit of the rocks under the conditions in which they exist. It would be generally agreed that the intensity of the strain is very important at moderate depths. But it is commonly supposed that rocks near the surface, and especially in little disturbed regions, are not under considerable strain; but that this conclusion is erroneous is shown by observations which have been made by a number of men. Niles has

shown[a] a high state of strain in the granite quarry at Monson, Mass. Before the quarry was opened it would not have been supposed that the rocks were subject to any unusual amount of stress, but when the quarry was opened the rocks were found to be in such a state of strain that frequent ruptures spontaneously took place, or occurred with very slight assistance by the quarrying operations. Before quarrying began the rocks were prevented from lateral expansion, but after an excavation was made they were freed from pressure on one side, and this loss of restraint led to the rupturing already mentioned. That the Monson granite is elastically compressed is shown by the fact that when a great mass is cut off from the sides of the quarry it expands so that the bisected drill holes do not match. Also elastic compression is shown by the expansion at various times during the quarrying, anticlinal arches thus being formed by the elevation of layers along horizontal planes of rupture. Johnston had previously described[b] similar spontaneous movements in the sandstone strata at Portland, Conn. Niles has also given[c] evidence of very important strain in the sandstone at Berea, Ohio, in the limestone of Lemont, Ill., and in quarries in Connecticut.

At various places in the Galena limestone of the Fox River Valley, Wisconsin, after excavation has been made, the layers have been found to be under such elastic strain that they have released themselves by expansion, forming anticlinal arches, in places 40 cm. in height.[d] Gilbert has described[e] post-Glacial anticlinal arches at various places in the Devonian shale of New York and northwestern Ohio and in the Trenton limestone of New York. It thus appears that the rocks in the upper part of the belt of cementation may be in a state of strain near or even to the elastic limit at many places throughout extensive regions. The condition of mechanical strain can be discovered only by quarrying processes, and by observations such as are given above. When a specimen is taken from a quarry in which

---

[a] Niles, W. H., Peculiar phenomena observed in quarrying: Proc. Boston Soc. Nat. Hist., vol. 14, 1871, pp. 1–8.

[b] Johnston, John, Notice of some spontaneous movements occasionally observed in the sandstone strata in one of the quarries at Portland, Conn.: Proc. Am. Assoc. Adv. Sci., 8th meeting, 1854, pp. 283–286.

[c] Niles, W. H., The geological agency of lateral pressure exhibited by certain movements of rocks: Proc. Boston Soc. Nat. Hist., vol. 18, 1876, pp. 272–284.

[d] Cramer, Frank, On a recent rock flexure: Am. Jour. Sci., 3d ser., vol. 39, 1890, pp. 220–225. Also, Cramer, Frank, On the rock fracture at the combined locks mill, Appleton, Wis.: ibid., 3d ser., vol. 41, 1891, pp. 432–434.

[e] Gilbert, G. K., Post-Glacial anticlinal ridges near Ripley and Caledonia, New York: Am. Geol., vol. 8, 1891, pp. 230–231.

the rocks are much strained, by that process it is largely relieved from strain, and a slide of it placed under the microscope may show little or no evidence of its former state of strain.

It therefore appears probable that a high state of strain is the common condition for the great mass of the rocks constituting the belt of cementation. It has been explained on pages 95–98 that in proportion as mineral particles are in a state of strain they are likely to be acted upon chemically by the ground solutions. Therefore the very general and marked state of strain in the rocks of the belt of cementation is probably a very important factor in their alteration. This is especially true of metasomatism. By that process, as explained on pages 690–692, the rocks may be released from strain, the mechanical energy producing the strain being utilized in promoting recrystallization. It is difficult or impossible to prove the importance of state of strain in metasomatism except by general reasoning, based upon the experimental facts referred to in Chapters III and VIII. But it is my confident belief that the general state of strain is one of the most important of the inciting causes of alteration.

STRAIN BEYOND ELASTIC LIMIT.

Strain beyond the elastic limit results in fracture. The belt of cementation belongs to the zone of fracture. It has been seen in the previous sections that deformation may be accomplished to a considerable extent by differential movement of the particles of incoherent rocks and by strain within the elastic limit. Where the rocks are coherent marked deformation in the belt of cementation is largely accomplished by fractures and by movements along the fracture planes. In the very partially indurated rocks fracturing may consist in the rupturing of the particles from one another, and adjustment come by differential movements between the particles. But in the coherent rocks the ruptures are wider spaced than the individual grains. In the weaker coherent rocks the surfaces of rupture are more or less irregular, ordinarily breaking around rather than cutting through the grains. This form of rupture is well illustrated by sandstones. The strongly coherent rocks usually show clean-cut fractures which cut the mineral particles.

When rocks in the belt of cementation are strained beyond the elastic limit there is a marked tendency for the ruptures to follow planes more or

less closely, and for the planes to be in parallel sets. In a given case there may be one or more of these parallel sets; commonly there are as many as three. In such instances the rocks are broken into parallelopiped blocks. In some instances there are as many as six or more parallel sets of ruptures, and by them the rocks are cut into various irregular forms.

The spacing of the different sets of ruptures is very variable. For instance, if there be three sets of ruptures, the distances between the fractures in one set may be several or many times as great as between those of another set. The spacing of all the sets in one case may be much wider than that of any set in another case. The fractures may be very far apart, as with widely separated faults or joints, or they may be very close together. In some instances the different sets of ruptures are so close together that it is scarcely possible to find an unruptured parallelopiped a centimeter in diameter. Ruptures of this kind are very well illustrated in the slates and graywackes of the Wausau district of Wisconsin. However, in the belt of cementation the ruptures are not so close as to cut all, or even any considerable proportion, of the mineral particles. Between the amount of rupturing necessary to produce particles a fraction of a centimeter across and that necessary to affect every mineral particle there is a very wide gap. In general, near the surface the ruptures are likely to be widely spaced, with considerable differential movement along the fractures. As depth increases, so that the rocks are subject to the weight of the superincumbent material, the ruptures are likely to be closer together. When the depth become so great that the fractures affect the individual mineral particles, the zone of anamorphism, or rock flowage, has been reached.

The fractures produced in rocks must take place as a result of tensile or compressive stresses.[a] Where the rocks are homogeneous and the fractures are by tensile stresses, they take place normal to the force. Where the fractures are by compressive stresses—and this is probably much more common—the ruptures are inclined to the direction of maximum compressive stress. Ignoring the effect of the stress, and supposing the rocks to be homogeneous, the ruptures would occur in sets at angles of 45° to the maximum stress. However, since the stress itself gives additional strength

[a] Becker, G. F., Finite homogeneous strain, flow, and rupture of rocks: Bull. Geol. Soc. America, vol. 4, 1893, pp. 48–49. Van Hise, C. R., Principles of North American pre-Cambrian geology: Sixteenth Ann. Rept. U. S. Geol. Survey, pt. 1, 1896, pp. 668–678.

in the direction of compression, the inclinations of rupture are inclined at angles less than 45° to the direction of greatest compressive stress.

The actual direction of fracture depends not only upon the direction and nature of the stresses, but upon the character of the rocks. The directions of rupture are greatly influenced by the variable strength of the rocks, by the rock structures and textures, and by the difference in size and strength of the constituent particles. Because of these varying factors force is transmitted with unequal efficiency in different directions. Consequently the direction of the maximum stress is not the same throughout a rock mass, but varies from place to place. This variability both in the nature of the rock and in the direction of the stresses gives very great irregularity of rupturing. Because of these variable factors no comprehensive statement can now be made as to the directions of ruptures in rocks; but certain special conclusions are evident. Where the rocks are heterogeneous the ruptures are likely to take place to a greater extent in the weaker rocks. Where there are contacts of strong and weak rocks ruptures are likely to take place at the contact planes, for these are planes of weakness. Where there are regular structures, such as bedding, gneissosity, schistosity, cleavage, the ruptures are likely to follow these planes of weakness. Where in a rock the particles have variable strength, weaker particles suffer more than the stronger ones. In the rupture of mineral particles fractures are likely to follow cleavage planes, since these are planes of weakness. All these factors result in giving ruptures which vary greatly from positions at right angles to tensile stresses and from 45° to the maximum compressive stresses.

It follows from the foregoing that the determination of the precise direction and nature of the forces which produced rupture in any individual rock is a most difficult matter.

After ruptures are produced differential movements may result in the rubbing of the parts adjacent to the fractures against one another. At such places the individual mineral particles may be granulated. However, this fracturing of the mineral particles is largely confined to thin layers along the walls of the openings. This fracturing of the particles is in many respects like the fracturing of mineral particles in the zone of anamorphism. (See pp. 673–675.) The matter is not further considered here.

From the foregoing it follows that deformation accomplished by fracture in the belt of cementation results in breaking up the rocks into great

masses by faulting, into blocks by jointing, into layers by fractures along bedding planes and other planes of weakness, into narrow slices by fissility, and into irregular fragments by brecciation. It has furthermore been seen that deformation produces comparatively unimportant changes in the size of the masses between the fractures. In these masses the original structures and textures are unaffected. But it will be explained under cementation, metasomatism, and injection, that the ruptures furnish conditions very favorable for these processes. Everywhere the ruptures give ready passages for the circulating ground water; everywhere they give ready entrance to intrusives. In consequence, the openings are closed by cementation and injection. Moreover, from the openings the water, frequently heated and loaded with material, is able to make its way for short distances in the subcapillary openings between the grains, and thus metasomatic processes are greatly promoted. Where the spacing of the fractures is small metasomatism may modify the unbroken masses throughout. Where the spacing of the ruptures is somewhat wide the metasomatic alterations may not extend all the way from one passage to another, and thus leave the interiors of the masses unaffected. Therefore there is very great variation in the amount of metasomatic alteration in passing from the walls of the openings to the interiors of the large unbroken masses. This has been fully worked out in connection with ore bodies, which commonly form along widely spaced, simple or complex, large openings. Lindgren especially has shown[a] how metasomatic processes greatly affect the walls of the fissures. The effect gradually dies out in passing away from the openings, but may be marked for some distance.

CHEMICAL WORK.

The chemical work in the belt of cementation needs consideration from two points of view—the chemical changes and the resulting processes.

CHEMICAL CHANGES.

The chemical work within the belt of cementation is accomplished mainly by water solutions. Water is here the great agent of metamorphism, but the igneous rocks are second only to water solutions. They

[a] Lindgren, Waldemar, Metasomatic processes in fissure veins: Trans. Am. Inst. Min. Eng., vol. 30, 1901, pp. 578–692.

are of vastly greater importance than in the belt of weathering. At the surface or within the belt of weathering, igneous rocks rapidly lose their heat, and thus produce a comparatively short-lived effect. Within the belt of cementation the igneous rocks retain their heat for a very long time. By their introduction they produce both a direct effect, due to their own action, and—far more important—an indirect effect by heating the solutions, and thus very greatly increase their efficiency both as to speed of reaction and as to quantity of material which can be held, as is fully explained elsewhere. (See pp. 79–81.)

The range of temperature at which the solutions work is from 0° C. to the critical temperature of water, which, as we have seen (pp. 566–569), is 365° C. The amount of work which the solutions accomplish in a given time at very high temperatures is almost indefinitely greater than that which is accomplished at lower temperatures. (See p. 79.)

The pressure at which the solutions work varies from that of an atmosphere to the pressure of a column of water to the bottom of the zone of fracture. Supposing the bottom of this zone of fracture to be at a depth of 10,000 meters, the maximum pressure would be 1,000 kilograms per square centimeter. Therefore the range of pressure upon the solutions within the belt of cementation is very great.

By observation we know that in the belt of cementation the important chemical reactions which take place as a result of the action of the various agents are oxidation, carbonation, hydration, and solution and deposition. These reactions are the same as those in the belt of weathering. Just as in the belt of weathering, the reactions of oxidation, carbonation, hydration, and possibly solution preponderate over the reverse reactions. However, the relative importance of these various reactions in the two belts is very different.

All of these reactions, as has been seen, are of very great consequence in the belt of weathering. Oxidation and carbonation are of much less consequence in the belt of cementation; but this statement can not be made of hydration, solution, and deposition. Hydration, because of the decreased prominence of oxidation and carbonation, becomes the chief one of these three processes in the belt of cementation. Solution and deposition are both of fundamental importance; but the first, solution, does not dominate as it does in the belt of weathering. All of these reactions have been fully

considered in Chapter VI on "The belt of weathering," and they will here be taken up only so far as their work is different in the belt of cementation from that in the belt of weathering. The modifications are easily made for oxidation, carbonation, and hydration and their reversals, but are complicated for solution and deposition.

In the upper part of the belt of cementation, that near the level of ground water, the active agents in the solutions are very similar to those in the belt of weathering, and therefore the reactions are closely allied to those of the belt of weathering. But as depth below the belt of weathering increases, the distinctions between the reactions which are of controlling importance in the two belts becomes more and more clear, and for the major part of the belt of cementation the relative importance of reactions is very different from that in the belt of weathering. The depth to which all the reactions of the belt of weathering extend into the belt of cementation depends very largely upon whether the waters for the particular area are ascending or descending. At places where large amounts of descending waters are converged, and where the variations of topography are marked, so as to give a very high head, all the reactions of the belt of weathering may be quantitatively important to depths of 800 or 1,000 meters or more, although such depths as these are very unusual. But where the descending currents are driven by a low head, some of the reactions of the belt of weathering may extend only to a very moderate depth into the belt of cementation. In areas where the water currents are ascending, and so continue to the belt of weathering, some of the reactions of the latter belt may extend scarcely at all into the belt of cementation. Oxidation, carbonation, hydration, and solution and deposition commonly do not take place separately, but occur at the same time upon the same materials; although, as pointed out on page 611, in the upper part of the belt of cementation, carbonation and oxidation are to some extent exclusive of each other. But for the purposes of analysis it is necessary to treat each separately.

OXIDATION.

Ordinarily when water passes from the belt of weathering into the belt of cementation it contains oxygen in solution. The amount of this oxygen may be as great as can be dissolved under atmospheric conditions of pressure and temperature, or the water may be saturated. From this the

amount varies to almost nothing. Also, in consequence of atmospheric pressure, oxygen may be forced into the sea of ground water to some extent. The favorable conditions for abundant oxygen in the water when it joins the belt of cementation are a very porous belt of weathering and absence of luxuriant vegetation. Under such conditions the atmosphere circulates somewhat freely through the belt of weathering, and as oxygen is exhausted in the belt by the processes of oxidation it is resupplied to the solutions by the atmosphere.

It is seen (pp. 609–610) that the sources of carbon dioxide are abundant, and therefore that the process of carbonation is almost universal in the belt of cementation. The situation is very different with oxygen. Practically the only oxygen supplied is that which is carried down by solutions from the belt of weathering and that which makes its way into the water of the belt of cementation at the level of ground water in consequence of atmospheric pressure. It naturally follows that, as the waters move downward and the process of oxidation continues, the amount of oxygen available becomes less and less. Commonly the oxygen is practically exhausted at very moderate depths. Therefore, while oxidation takes place within the belt of cementation wherever oxygen is available, for much of the belt there is no oxygen available for this process and hence oxidation does not occur. This general reasoning is plainly confirmed by observation. The waters of the upper part of the belt of cementation are commonly oxidizing, while the deeper waters of the belt rarely contain oxygen. According with this general observation, Lepsius has made exact experimental tests of the amount of oxygen in waters derived from bore holes, and he finds that with increase of depth there is a gradual and somewhat uniform decrease of oxygen contained in the ground waters.[a] Bischof many years ago verified the depletion of oxygen as the result of oxidation by determinations of the relative amounts of oxygen and nitrogen in springs. He found in cold springs that the oxygen is not so great in proportion to the nitrogen present as in the atmosphere, and in warm springs this deficiency is even more marked, and he correctly explains this deficiency as due to the "partial combination of this gas with oxidizable substances."[b]

---

[a] Berichte Deutsch. chem. Gesell., vol. 18, 1885, p. 2487.

[b] Bischof, Gustav, Elements of chemical and physical geology, translated by Paul and Drummond, Harrison & Sons, London, 1854, vol. 1, p. 234.

Under ordinary circumstances oxygen is practically exhausted in the early part of the journey, so that it is rather unusual for marked oxidation to extend more than a few meters below the level of ground water. But where, because of marked relief, there are large and strong downward-moving currents through open and porous rocks, the process of oxidation may extend to a very considerable depth into the belt of cementation. This has been especially noticed in mining regions, where ore deposits are commonly located along joints, faults, or other trunk channels where there are numerous and large openings. One of the best illustrations of oxidation extending to a considerable depth is that furnished by the iron ores of the Lake Superior region. Here, as fully explained in the chapter on ore deposits, the process of oxidation has extended on a very great scale to the depth of 100 meters, in mines has produced great ore bodies to a depth of 300 meters, and exceptionally has gone on to an important extent to a depth of 500 to 700 meters. As an instance in which oxidation has extended to a great depth may be mentioned the San Juan district of Colorado. Here in some of the mines oxidation is marked to a depth of 600 meters, and is occasionally noticeable to a depth of 1,000 meters. In contrast with such regions as these are others in which the water ascends almost or quite to the surface. In such instances oxidation scarcely extends below the level of ground water. An excellent illustration of this is furnished by the Missouri-Kansas lead and zinc district.

The oxygen is chiefly utilized in the oxidation of iron, sulphur, and organic material. In the upper part of the belt, where oxygen is abundant, large amounts of hematite and limonite may be produced by the oxidation of the ferrous particles, but for the greater part of the belt of cementation, where oxygen is somewhat deficient, the ferrous oxide is oxidized only to the form of magnetite, since this requires, per unit of iron, only two-thirds as much oxygen as to produce hematite and limonite.

The sulphur is mainly united with the iron as pyrite and marcasite. At the same time the sulphur is oxidized the iron also is oxidized. Where the oxygen is abundant there may be produced ferrous sulphate, or ferric oxide and sulphuric acid; but where oxygen is not abundant, as in the major portion of the belt, magnetite and sulphurous acid are more likely to be formed.

Where the oxygen is utilized in the oxidation of organic material carbon dioxide and water are produced, and these compounds join the

circulating ground water. In many cases the major portion of the oxygen is thus utilized. In so far as this takes place the process leaves no direct evidence of itself by the existence of oxides. So far as suphuric acid is formed the same is true. The carbonic acid and the sulphuric acid may remain in part in the belt of cementation in carbonates and sulphates. So far as this occurs the oxidized compounds remain in the belt, but not as substances which we ordinarily think of as evidences of the process of oxidation.

After the oxygen of the waters of the belt of cementation is exhausted organic and other compounds, such as sulphides, are likely to be taken into solution, which renders the waters reducing, as explained on page 165. The waters under impervious strata which take a long underground journey are especially likely to be in this condition, for such a journey furnishes ample time for the complete consumption of the oxygen contained in the solutions. The above is illustrated by the deep artesian waters of many parts of the world. Excellent cases are those furnished by the artesian waters of the Potsdam sandstone of Wisconsin and the Dakota sandstone of the James River Valley, Dakota. The waters which issue from the Potsdam formation along Lake Michigan are of a reducing character, containing, as noted by Chamberlin, some hydrogen sulphide.[a]

Where the waters become reducing deoxidation of the compounds with which they come into contact may take place.

One form of deoxidation is of sufficient consequence to require mention. While of no great quantitative importance, it is important from the point of view of the metallic ores. It has been explained under "The belt of weathering" (pp. 468–469) that the sulphides are continuously oxidized to sulphites or sulphates. A part of the sulphurous and sulphuric acid united with the original elements, or with other elements, joins the belt of cementation. After the oxygen is exhausted and organic compounds are present the sulphites and sulphates may be reduced to sulphides by the direct action of the organic matter, or by these compounds after passing into the solutions.

The process of reduction, or deoxidation, of the sulphates involves the oxidation of the organic material, and thus this reaction, from one point of view only, is reduction. From the other point of view it is oxidation.

---

[a] Chamberlin, T. C., The ore deposits of southwestern Wisconsin: Geol. of Wisconsin, vol. 4, 1882, p. 547.

Thus the process of deoxidation or reduction, so far as it takes place, involves the passage of the oxygen abstracted to the reducing agents or their oxidation. Moreover, the sum total of the heat effect, taking into account both the reduction and the oxidation, is to liberate heat. Hence the reaction is one normal for the zone of katamorphism. The sulphides formed may be precipitated and serve as one of the subordinate cementing substances. The formation and precipitation of sulphides will be much more fully considered in Chapter XII, on "Ore deposits."

We have just seen that deoxidation, so far as it takes place, is explained by oxidation of some other compound. But oxidation by the oxygen originally derived from the surface and present in the solution does not involve the deoxidation of some other compound. It therefore follows that the process of oxidation in the belt of cementation overbalances that of reduction in the belt by the amount of oxygen which is carried into the belt of cementation by the entering waters, and is abstracted from it by the union of the oxygen with the compounds encountered during its underground journey.

It has been explained on page 467 that the process of oxidation of inorganic compounds involves increase of volume varying under ordinary circumstances from a small amount to as much as 64 per cent. But by the oxidation of the carbonates carbon dioxide is liberated, and this may give a considerable decrease in the volume of the product, amounting in some instances to as much as 50 per cent.

In summary, it is clear that oxidation is a reaction characteristic of the belt of cementation, but that in this belt it has no such importance as in the belt of weathering. In the belt of cementation oxidation goes on but to a very limited extent. While in the upper part of the belt great masses of highly oxidized rocks are locally found, as in the case of iron ores, for the major part of the belt the evidences of oxidation are not apparent, it being evidenced perhaps to the greatest extent by magnetite.

CARBONATION.

The water which passes from the belt of weathering to the belt of cementation carries dissolved carbon dioxide precisely as it does oxygen. The quantity thus carried varies from an exceedingly small amount to sufficient to produce saturation.

It has been fully explained on pages 473–475 that carbon dioxide is produced in large quantities in regions of abundant vegetation, where the process of oxidation of carbon goes on on a great scale in the belt of weathering. Therefore, the conditions for abundant carbonic acid in the waters joining the belt of cementation are those of luxuriant vegetation. It has just been explained that the conditions favorable for the transportation of abundant oxygen to the belt of cementation are those of open soil and lack of vegetation. Hence, the waters which carry carbonic acid plentifully to the belt of cementation are not likely to carry oxygen plentifully. Where one is abundant the other is likely to be deficient It has just been explained that the process of oxidation may take place upon carbonates. Also, by oxidation of organic matter which has been so deeply buried as to be within the belt of cementation, carbon dioxide is formed. In so far as these occur carbon dioxide is produced by the reactions within the belt of cementation itself, and thus is added to the ground solutions. It thus appears that the occurrence of one of the chemical processes within the belt of cementation, that of oxidation, by its very action produces another active agent, carbon dioxide, and therefore promotes the second of the important reactions of the belt of cementation, that of carbonation.

The third source of carbon dioxide for the belt of cementation, as is fully explained in the following chapter (pp. 677–679), is the process of silication, with simultaneous decarbonation as a prominent and often a dominant reaction. Some of the liberated carbon dioxide is permanently retained in the zone of anamorphism as occluded gas and liquid. (See p. 678.) But the temperatures of the zone of anamorphism are above the critical temperature of carbon dioxide. This compound is therefore originally a gas, and is capable of making its way through very small openings. Doubtless a considerable amount of it escapes from the zone of anamorphism and enters the belt of cementation. Thus is largely explained the abundant carbonic acid which is frequently found in the waters of deep mines rising from a still deeper source.

It therefore appears that the waters of the belt of cementation have four important sources of carbon dioxide—from the belt of weathering, from the decomposition of carbonates of the belt of cementation through oxidation, from the oxidation of organic material within the belt of cemen-

tation, and from the silication of carbonates in the zone of anamorphism. Therefore, the carbon dioxide for carbonation in the belt of cementation is contributed by the belt of weathering above, by the zone of anamorphism below, and by the belt of cementation itself.

Bischof fully realized the very great abundance of carbonic acid in "a numerous class of springs which are abundantly distributed over the surface of the earth, especially in districts where extinct volcanoes or basaltic rocks occur."[a] He also notes that "carbonated springs which evolve abundance of this gas are likewise met with in the midst of sedimentary formations."[b] The locations of a very large number of carbonated springs scattered through extensive regions are mentioned.[c] Bischof further says that the carbonated springs "are always situated at the lower part of mountain declivities or at the deepest points of valleys, generally near brooks;" while "fresh-water springs issue at points still higher above the bottom of the valley, and sometimes at tolerably considerable heights."[d] He further fully realized that the springs bringing the carbonic acid abundantly to the surface are deep-seated waters which have arisen from considerable depths.[e] Finally, Bischof attributes the abundance of carbonic acid in the waters of deep springs and those which come from deep borings to the silication of the carbonates. However, he recognizes that the carbonic acid found in the waters of wells is also produced in part by the oxidation of organic material.[f] Bischof therefore many years ago correctly gave two main sources of carbon dioxide for the water of the belt of cementation.

It has been fully explained on pages 160–161 that, under the conditions of the belt of cementation, where the rocks support themselves and openings exist, the reactions take place which liberate heat. Carbonation of the silicates and oxides belongs to this class. (See pp. 475–480.) It therefore follows from general reasoning that the carbon dioxide abundantly supplied to the waters of the belt of cementation will react upon various compounds and produce carbonates. Of the compounds upon which it acts

[a] Bischof, Gustav, Elements of chemical and physical geology, trans. by Paul and Drummond, Harrison & Sons, London, 1854, p. 217.

[b] Bischof, cit., vol. 1, p. 217.

[c] Bischof, cit., vol. 1, pp. 218–241.

[d] Bischof, cit., vol. 1, p. 223.

[e] Bischof, cit., vol. 1, pp. 228–230.

[f] Bischof, cit., vol. 1, p. 239.

the silicates are undoubtedly those of dominant importance. The action of carbonic acid upon the silicates results in the production of carbonates of the bases and the liberation of silica, which may remain in situ as quartz or go into solution as colloidal silicic acid. Monoxides of iron and manganese originally present in this form or produced by the oxidation of sulphides may unite with the carbon dioxide and form carbonates.

Since the carbon dioxide of the belt of cementation is derived from above, from below, and, by reactions of oxidation, from within the belt, one would expect carbonation to take place throughout the belt of cementation. In the upper part of the belt of cementation the main source of supply of carbon dioxide is that from the belt of weathering; but, as has been noted, where the carbon dioxide is abundant oxygen is apt to be deficient, so that where one finds active carbonation in the upper part of the belt of cementation one would not expect to find active oxidation.

The majority of the carbonates formed, and those originally present in the belt of cementation, are rather soluble. Commonly, therefore, the waters issuing from the belt of cementation contain very large amounts of carbonates and carbon dioxide. Average amounts of carbonates given by Peale from many mineral springs from various portions of the United States are as follows:[a]

	Grains per gallon.	Milligrams per liter.
North Atlantic States	32.88	56.27
South Atlantic States	13.70	23.45
North Central States	45.35	77.62
South Central States	18.30	31.32
Western States	139.59	238.90

Carbonic acid is a very much less active agent than oxygen. The process of carbonation therefore takes place slowly, and the carbonic acid does not all succeed in getting united with the bases. In many instances the amount which has failed to unite with the bases is large. This is illustrated by the abundance of uncombined carbon dioxide in the waters of many of the famous springs of the world, as those of Carlsbad and Shasta, and also by the great abundance of uncombined carbon dioxide noted in connection with the rising waters of many mines.

It has been explained under "The belt of weathering" that the increase in volume in the process of carbonation of the silicates, provided

[a] Peale, A. C., Lists and analyses of the mineral springs of the United States: Bull. U. S. Geol. Survey No. 32, 1886, pp. 1–235.

the liberated silica remains in situ, varies in most cases from 15 to 50 per cent. If, therefore, the carbonates produced and the silica liberated be deposited, there is great increase in volume.

While in the belt of cementation carbonation unquestionably dominates over decarbonation, doubtless it frequently happens during earth movements that the pressure is so great that silication and decarbonation take place.

HYDRATION.

It has been stated that the belt of cementation might almost equally well be called the belt of saturation. Water is everywhere present. The process of hydration is one which involves a great increase of volume, but openings exist which may be utilized by the process without overcoming the strength of the rocks or gravity. Therefore the conditions are ideal for hydration, and this everywhere occurs. Indeed, it is in the belt of cementation that the great group of hydrous silicates form most abundantly. The belt of cementation is the home of the hydromicas, of the chlorites, of the zeolites, of serpentine, of the epidotes, and of limonite and gibbsite. Kaolin and talc also form there, although they are more especially characteristic of the belt of weathering. The increase in volume in these processes of hydration, provided all the compounds remain in situ, varies in most cases from 20 to 50 per cent. While, as already explained, oxidation and carbonation are important in the belt of cementation, the process of hydration occurs on a vastly greater scale, and the chief change in volume in this belt is due to this process.

Just as decarbonation may take place under conditions of exceptional pressure in the belt of cementation, so dehydration may, and certainly does, occur, although this is so subordinate to the process of hydration as almost to be negligible.

SOLUTION AND DEPOSITION.

Both solution and deposition are processes of great importance in the belt of cementation. We have already seen that deposition occurs on so great a scale as to make the filling of the cavities and consequent cementing of the rocks the rule. While at first thought it might be supposed that solution is subordinate, a close analysis shows that this process is not less important than deposition, and, indeed, it may more than balance deposition.

QUANTITATIVE RELATIONS BETWEEN SOLUTION AND DEPOSITION.

It has been fully explained that the belt of weathering at any given time represents the partly disintegrated and decomposed material above the level of ground water. During the long-continued erosion of a region the belt of weathering steadily migrates downward. Thus the forces of weathering continually find new material at the bottom of the belt upon which to work. Therefore, as denudation goes on, there is always a belt of a certain thickness in which weathering processes are taking place. These include solution as a dominant process. It has further been noted that the material abstracted from the belt of weathering is divided into two parts, one of which goes to the overground circulation and thence to the sea, the other of which passes through the belt of weathering into the belt of cementation below. Each unit of water which passes downward through the belt of weathering into the belt of cementation carries with it in solution a certain amount of material. As a consequence of continuous downward migration of the belt of weathering, it is certain that an increment of material is continuously added to the belt of cementation from the belt of weathering.

If this increment which the sea of underground water continually receives were deposited in the belt of cementation, it would furnish a sufficient supply of material for the cementation of that belt. Much of this material is certainly deposited in the belt of cementation, but in that belt solution is also taking place, and the question therefore arises whether or not more material is deposited than is dissolved in the belt of cementation. This question is not easy to answer, but we know certain data which have an important bearing upon it.

One of the fundamental conclusions worked out in Chapter III, on "The agents of metamorphism," is that the quantity of water which passes through the belt of weathering and enters the sea of underground water is substantially equal to that which emerges from this sea through springs and through seepage and joins the run-off. If we knew the relative amounts of material contained in solution in the waters entering and issuing from the belt of cementation, we could answer the third question—i. e., whether more material is dissolved or deposited in the belt of cementation. But the only possible way to get this information is by numerous analyses.

In various regions the amounts of salts should be determined in the solutions near the bottom of the belt of weathering and in the solutions issuing from the belt of cementation. Such a comparative analytical study has not been made, and we must therefore have recourse to general reasoning for a probable answer to the question of the relative amounts of the salts entering and issuing from the belt of cementation.

It might be concluded that the actual fact of widespread consolidation due to filling the openings of the belt of cementation, so fully emphasized in the opening pages of this chapter, is evidence that the amount of material contained in the water issuing from the belt is not so great as that which joins it through percolation. But there are considerations which render this view very doubtful. As shown by numerous analyses, it is certain that large amounts of materials are contained in the spring and seepage waters which issue from the belt of cementation. From general considerations, if the character of the compounds transported be ignored, one would expect that this amount would be greater than that which entered the belt. These considerations are as follows:

As water passes through the belt of weathering and enters the belt of cementation it may not have been sufficiently long in the belt of weathering and in close enough contact with the various compounds to become saturated. Doubtless in many cases of fine soils containing plentiful soluble compounds, where vegetation is abundant and percolation is slow, saturation for many of the compounds may be approached or even attained. But where there are coarse and thin soils underlain by fissured or porous material, it is highly probable that the descending waters are far from saturated when they leave the belt of weathering and join the belt of cementation. After the waters join the belt of cementation they take a longer or shorter journey before issuing at the surface. It has been explained (pp. 584–586) that the general movement of the ground water is exceedingly slow. In many instances also its journey is long—in some areas hundreds of kilometers. In this connection it may be recalled that it was calculated that the waters which issue at Chicago probably entered the ground in central Wisconsin somewhere from one hundred and fifty to two hundred and fifty years before This factor of time, therefore, is of fundamental consequence in the work of the water of the belt of cementation, and it would be strange if the water which has taken a considerable

journey in a formation, even if but a small fraction of that in the case mentioned, should not become saturated with the compounds with which it is in contact.

The journey of the water in the belt of cementation involves a component parallel to the surface and a vertical component. As a result of the component of the movement of ground water parallel to the surface there is a tendency for material to be taken into solution and to be abstracted by the water. For a given depth the pressure and the temperature are, on the average, the same. The longer this course the nearer will the water approach to saturation with the compounds with which it is in contact, because of the time factor. If the journey be long, the state of saturation may be attained at a comparatively early stage, after which the additions and subtractions of material may be presumed, on the average, to neutralize each other, although in a given instance the total amount of material held in solution would vary greatly, depending upon the character of the rocks with which the water is in contact.

Under normal conditions, so far as the vertical component is concerned there is steadily increasing pressure and temperature during the downward movement, and steadily decreasing pressure and temperature during the upward movement. If the places of entrance and issue were at the same level, these two factors might be considered to neutralize each other, but the descending column is necessarily the longer; therefore the balance of the two processes is in favor of solution rather than deposition. Also, unless the water has become saturated during its descent solution will continue during its ascent until saturation is attained, and if the vertical component be short, this may not occur before the entire ascent has been made.

Finally, the temperature of the entering and issuing water is of great consequence in the matter of relative quantities of dissolved and deposited materials. Even if the temperature were precisely the same at the entering and issuing points this would favor solution, for increase in temperature as the water descends very greatly accelerates the process of solution, and as the water ascends precipitation takes place only when saturation is reached, and then only to an extent sufficient to prevent supersaturation.

But into this matter of temperature another very important factor enters. It has been shown on pages 589–592 that, on the average, the temperature of the issuing water is higher than that of the entering water.

It has been fully explained on pages 79–81 how important a slight increase in temperature is, not only in respect to the speed with which material is dissolved, but in respect to the quantity which may be taken into solution before saturation is reached. This small average additional increment of heat in the issuing water over that of the entering water is very favorable to the presence in the issuing water of larger amounts of material than was contained by the entering water.

Therefore it appears that, in proportion as the underground journey of the water in the belt of cementation is slow, in so far as it has a horizontal course, in so far as it enters at a higher elevation than it issues, and in so far as it issues at a higher temperature than it enters, it should contain more material in solution per unit mass when it issues than when it enters. From all these points of view it is to be expected that ground waters contain more material in solution when they issue from the belt of cementation than they contained when they entered that belt, and that waters which have taken a journey of considerable length in a uniform formation will have reached a state of almost complete equilibrium between themselves and the surrounding rocks, or will be saturated.

But another important factor enters into the matter. It is not to be supposed that during the underground journey the materials which are held in solution are the same. Throughout the journey there are various chemical interactions. Much of the material brought from the belt of weathering is deposited; there is solution of material at a certain place, and later deposition of it elsewhere; there is interaction between the solutions and solids; there is interaction between the mingled solutions from different sources.

It is the uncertainty as to the average effect of these various chemical reactions that leaves us in doubt as to the end result; that is, whether or not the solutions of all systems of circulation are, on the average, richer in material when they emerge from the belt of cementation than when they entered it. For instance, if a solution containing oxygen were mingled with a solution in which iron was the chief base, hematite or limonite would be precipitated, and the solution would be depleted in material even if the temperature of the water were higher at the end than at the beginning of the journey. Again, colloidal silicic acid is readily soluble even at low temperatures, but the acid has a marked tendency to decompose into water and silica, though the reaction is a slow one. So far as it takes place in the

belt of cementation, there is precipitation of quartz and reduction of the amount of material held in solution, even if the temperature be high. Indeed, it is not improbable that high temperature is favorable to the dehydration of silicic acid.[a] Because of the uncertainty of the effect of the chemical reactions, one can not say whether more material emerges with the solutions than enters with them. Were it not for the enormous quantity of colloidal silicic acid contributed by the belt of weathering and the dominant importance of quartz as a cement (see pp. 622–623), probably solution due to the causes above assigned would overbalance deposition. But in the present state of knowledge I must leave unanswered the question as to which of the processes, solution or deposition, is preponderant in the belt of cementation. Both are of the utmost consequence.

Concluding, we now see that the unity of the belt of cementation and the belt of weathering from a physical-chemical point of view is perfect. Both are belts of oxidation, carbonation, hydration, and solution and deposition. Both are belts of reactions with liberation of heat and expansion of volume. The contrast between the two belts is largely due to the variable quantitative value of each of these processes in the two belts and the resulting condition in which the rocks are left—disintegrated and softened in the one and cemented and indurated in the other.

RESULTANT PROCESSES.

The processes resulting from the chemical changes are cementation and metasomatism.

CEMENTATION.

By cementation is meant the binding together of the rock particles by deposition of material as minerals in the interstices of the rocks. In the previous chapter on "The Belt of Weathering," we ascertained the source and character of the materials which joined the sea of ground water and which are therefore available for cementation in the belt of induration. It is clear that there are constantly being added from the belt of weathering to the continuous sheet of water in the belt of cementation the following compounds: Sodium, potassium, calcium, magnesium, iron, aluminum, as carbonate, sulphate, nitrate, phosphate, chloride. With these there are also

[a] Mendeléeff, D., Principles of chemistry, trans. by George Kamensky, Longmans, Green & Co., London, 1897, vol. 2, p. 112.

abundant colloidal silicic acid and lesser proportions of the rarer bases and acids, such as manganese, hydrofluoric, and boric. In the following section on metasomatism it will be shown that during the alterations of the materials of the belt of cementation equal or greater amounts of these compounds are added to the solutions. A portion of the great amount of material which joins the sea of ground water from the belt of weathering and from the alterations of the minerals of the belt of cementation is there precipitated as minerals and the rocks are cemented. Hence the name, "belt of cementation."

It will be remembered that the openings in rocks comprise those between the mineral particles, and especially the grains of sediments, the vacuoles of igneous rocks, the regular openings of fissility, joints, and faults, and the irregular openings from those of the fractures of the individual mineral particles to those of breccias. Further, it will be recalled that the amount of openings varies from a small fraction of 1 per cent to 75 per cent, that in the mechanical sediments and the porous lavas a pore space of 20 to 40 per cent is common, and that the quantitative importance of the fault, joint, and fissile openings is great. (See pp. 124–131.) Therefore the amount of material which is required to fill the openings of great formations, thousands of meters in thickness and extending over areas of hundreds or thousands of square kilometers, is vast. Yet it is rather rare, if not unknown, for a rock which has been deeply buried and approaches the surface by denudation not to have the older openings of all kinds almost entirely filled.

In proportion as the process of cementation advances it necessarily follows that the openings become smaller, the circulation of the water is retarded, material is transported in smaller quantity, and the process becomes slower. This lessening of speed continues from the first, and when cementation is near completion it must be exceedingly slow. Notwithstanding this the process, as has been explained, has been practically completed for great thicknesses of rocks over extensive areas. The time required for the work must have been great, and yet for completion under favorable conditions it is certain that it does not require geological eras. This is shown by the complete cementation of formations of Eocene age In such instances the process must have been completed and a sufficient time have elapsed for erosion to bring the cemented rock

to the surface since early in Tertiary time. The best illustration known to me of a completely cemented great formation of Tertiary age is the San Juan breccias of Colorado. This formation is 1,500 meters thick; it was very porous, and yet every ancient opening not of microscopic size, from great fissures to pores between the particles of ash, is completely filled.

Of course, after cementation has been partially or wholly completed orogenic movements may occur which produce a new set of openings, and a vigorous circulation be set up in the new openings. This would give new trunk channels for circulation and thus assist in the cementation of partially closed old openings.

In judging of the nearness to completion of the process of cementation when the rocks were at a considerable distance below the surface, openings which have been produced by later orogenic movements when the rocks were nearing the surface must be ignored. Commonly such openings are not closed.

It is explained on pages 595–597, 646–648 that the openings in the rocks are to some extent closed by pressure, and locally are closed by injection. So far as these processes take place the space left to be filled by the process of cementation is decreased; but the residual actually observed to have been filled by the process of cementation is enormous.

In the cementation of the openings between the mineral particles the new mineral material may be added in two different ways. It may attach itself to the old grains of like mineral character, or it may be deposited as independent interstitial material. If mineral particles be fractured, it may heal them with the same or some other mineral.

When interstitial mineral material attaches itself to an old mineral of like character, the two being in optical continuity, the mineral is said to have been enlarged. The principle explaining the enlargement of old mineral particles rather than the development of new smaller mineral particles is essentially the same as that explained on pages 74–76, that large individuals grow at the expense of small ones. Where there are old nuclei which can be used the solutions deposit material upon these; for if independent particles begin to form, these under the principle above referred to would be likely to be again dissolved and deposited upon the old larger particles. The enlargement process is far more important for quartz than for any other mineral, although enlargements of feldspar, hornblende, augite, biotite,

calcite, garnet, and tourmaline have been observed, some of them frequently. In a clastic rock the process of enlargement means that the component grains are minerals still and have the structure and potency of minerals. These minerals, originally produced in igneous or metamorphic rocks, are taken from their original positions and deposited in a secondary rock. The beds are buried by overlying formations. Mineral-bearing solutions pass through the new rock and each mineral fragment chooses from the solutions material like itself. This it attaches to itself in optical continuity, even though the time interval between the first and second growths be indefinitely long. In the early stages of this renewed growth crystal faces are often rebuilt. (Pl. IX, *A*.) If the growth continues, the enlargement of a particle meets similar enlargements from other grains. By further growth these interlock and finally fill up all the interspaces and perfectly indurate the rock. (Pl. IX, *B*.)

FIG. 13.—Part of a thin section of a quartz-schist showing liquid- and gas-filled cavities of a secondary nature. Black Hills, South Dakota.

This process of enlargement is of greatest importance in the mechanical sedimentary rocks. Its magnitude in these rocks is fully explained on pages 865–868. The process is also important in the volcanic fragmental rocks, including both coarse tuffs and ashes; and, finally, the process does take place, although it is of subordinate importance, in massive igneous rocks. The cracks within and between the grains may be cemented by substances the same as or different from the materials cemented. If the cementation be imperfect secondary gas- or liquid-filled cavities may be formed. Often the broken fragments are somewhat displaced, but occasionally, in the case of parallel fractures, the particles are broken apart and left very nearly in their original relative positions, in which case the healing may be so perfect that the fact that the rock has been fractured may be shown only by the gas- or liquid-filled cavities and by the secondary inclusions. Thus are explained many of the inclusions in cavities which are so frequently noticed to occur along regular parallel planes. (See fig. 13.)

In all cases where the process of cementation has gone far the deposited minerals interlock, and in the larger spaces they may have a coarsely crystalline texture. The quantity of cementing material varies in different

cases from a relatively unimportant amount to predominance. The cementing minerals may permeate the rocks through and through, and fill all the interspaces, microscopic and macroscopic. The result is in many instances to give a most extraordinarily complex structure, the places between the original minerals being filled, the parallel fractures being emphasized by the parallel impregnation, and the whole being intersected by larger masses of holocrystalline interlocking mineral materials, some of which are parallel to the original structures, some of which are diagonal to them, and some of which are parallel for a certain distance and then cut across them. The material filling the larger crevices often has distinct vein-like forms. (Pl. II, *A*.) When examined carefully the material deposited parallel to laminated rocks may be found to follow the folia very closely, or it may be found to follow along them for some distance, then break across one or more, and then follow them again. In proportion as the cementing material follows the laminæ the cement bands are likely to be of approximately the same width. In proportion as there is a tendency for the material to break across the folia the veins usually are of unequal size.

The cementing minerals filling the openings of fissile rocks are usually different or in different proportions from the minerals of the adjacent laminæ, and hence there is a tendency to preserve and emphasize the laminated arrangement. Where sets of parallel joints are filled, for a similar reason a parallel structure is produced. Where there are intersecting sets of parallel joints the parallel structures of cementation may form simultaneously in two or three directions. It therefore follows that where the openings are of the sheeted parallel kind, in general the process of cementation results in a regular alternation of parallel layers of different kinds, the structures of which have no definite relations to the original bedding.

CEMENTING SUBSTANCES.

The more important cements of rocks may be divided into oxides, carbonates, silicates, and sulphides.

The most important oxides are silica, iron oxide, and aluminum oxide. The more important carbonates are calcite, dolomite, and siderite. The silicates include both the hydrous and anhydrous silicates, but the former are by far the more important. The only sulphides which are geologically

important are marcasite and pyrite, but from the point of view of ore deposits many other sulphides are of great consequence.

In addition to these, there are many subordinate minerals deposited in the belt of cementation; indeed, almost every mineral which occurs in rocks may there form, but the amounts are so small that they will not be considered here.

OXIDES.

Silica.—Silica may be deposited as opal, chalcedony, or quartz. In the process of precipitation it may fill any of the classes of openings which exist in rocks. But the greatest quantity of this material is deposited between grains of sediments, and especially between the grains of quartzose sand. Sandstone formations are one of the most abundant of the sedimentary deposits. It has been shown on pages 124–126 that the original pore space of such formations probably varied from one-fifth to two-fifths of the volume, with a probable average of approximately one-third. The ordinary quartzites which have not been modified by mechanical action are completely indurated by the deposition of quartz between the grains, in orientation with the original grains, or as independent material, or the two combined (Pl. IX.) The volume of quartzite of this class now existing upon the earth is very great. (See pp. 865–868.) In reaching a judgment as to the amount of quartz which has been precipitated in sand, it must be remembered also that many sandstone and quartzite formations produced in past geological times have been destroyed by the forces of erosion and redeposited.

One of the reasons why quartz is so very extensively deposited in quartzose sandstone is furnished by the principle (see pp. 120–122) that, other things being equal, material in solution is precipitated where there are nuclei of the same composition upon which it may be deposited. The innumerable rounded grains of quartz in the sands furnish the necessary nuclei which promote the precipitation of silica.

But quartz is deposited not only between the grains of quartzose sands; to some extent it is deposited between the grains of all other porous mechanical sediments, although the amount thus precipitated is subordinate. A vast amount of quartz is also deposited in the vacuoles of volcanic rocks as amygdules. Further, silica is deposited in the innumerable openings of the fissile rocks, in the numberless joints, and along the numerous faults

and openings in the brecciated rocks. The amount thus deposited is only second to that deposited in the sediments. Finally, as shown in the succeeding section on metasomatism, there are very extensive replacement deposits of quartz. There is no means by which the amount of replacement silica can be measured, but the quantity is certainly very great.

The foregoing facts give us some idea of the vastness of the amount of siliceous material which is deposited in the belt of cementation. Certainly the amount is to be measured in thousands and probably in hundreds of thousands of cubic kilometers. An adequate source of this silica is that liberated by the process of carbonation in the belt of weathering. (See p. 480.)

Iron oxides.—Iron oxide is extensively deposited between the grains of mechanical sediments, and therefore is an important cementing agent Iron oxide is also deposited in the other classes of openings in rocks, and also as a replacement product. Iron oxide is deposited as magnetite, hematite, limonite, and other hydrated oxides.

A very large amount of the iron is precipitated as hematite or limonite or other hydrated oxide. This precipitation is likely to occur where oxygen is abundant. These conditions are likely to obtain where solutions from different sources are united in some main channel of descending ground water. No better illustration of precipitation of iron oxide by this process can be given than the great hematite deposits of the Lake Superior region, which are precipitated by the mingling of waters bearing iron carbonate and those bearing oxygen. (See pp. 1194–1197.)

Magnetite is deposited in the belt of cementation as a very widespread constituent. The explanation of the precipitation of some magnetite is: In the belt of cementation there is usually a deficiency of oxygen. If the iron be supposed to be carried in the form of carbonate, the reaction for the precipitation of magnetite may be written as follows:

$$3FeCO_3+O=Fe_3O_4+3CO_2.$$

Other methods by which magnetite is precipitated are considered on pages 845–846. Where iron is thrown down as magnetite it is ordinarily found in crystals. As illustrations of this may be mentioned formations in the Lake Superior region, some of which are of economic importance, as, for instance, the magnetite of the Michigamme, Republic, and other mines

along the Republic trough. However, the magnetite thus deposited in solid bodies is entirely subordinate to the vast amount which is disseminated through the rocks of the adjacent formations—the quartzites, slates, and tuffs. Extensive deposition of magnetite is illustrated by the Michigamme schist of the Marquette district and by the Hemlock volcanic formation of the Crystal Falls district.[a]

It will be remembered that hematite and limonite are very abundantly precipitated in the belt of weathering as well as in the belt of cementation, but magnetite very rarely forms in the belt of weathering. It therefore appears that magnetite cement is especially characteristic of the belt of cementation.

Aluminum oxides.—The aluminum oxides which are deposited as cementing substances are gibbsite, diaspore, and perhaps corundum. Both of the hydrous minerals are known to be rather frequent cementing constituents where the rocks are of an intermediate or basic character. Usually they have not been regarded as important cementing minerals, but I suspect they are rather more plentiful than has been supposed. My reason for this belief is the frequency with which aluminum hydroxide is a by-product in the common alterations of such minerals as the feldspars, feldspathoids, micas, and other minerals. (See pp. 375–394.)

CARBONATES.

The important carbonate cements are calcite, dolomite, and siderite.

Calcite and dolomite.—Calcite and dolomite are treated together, since without chemical analyses it is usually impracticable to discriminate between the two where deposited in rocks. Also, there are various gradations between calcite and dolomite. In general, it may be said that these minerals are deposited in all the kinds of openings in rocks. They are more likely to be extensively deposited in the calcareous rocks than in the siliceous rocks, since in such rocks the solutions are sure to contain abundant carbonates, and there are crystals of calcite and dolomite to serve as nuclei for deposition. The calcium carbonate and magnesium carbonate may be deposited upon calcite and dolomite, respectively, thus enlarging these minerals precisely

[a] Van Hise, C. R., and Bayley, W. S., The Marquette iron-bearing district of Michigan: Mon. U. S. Geol. Survey, vol. 28, 1897, pp. 444–452. Clements, J. Morgan, and Smyth, H. L., The Crystal Falls iron-bearing district of Michigan: Mon. U. S. Geol. Survey, vol. 36, 1899, pp. 150–152.

as quartz is enlarged. The deposition of magnesium carbonate in many cases involves the solution of an equivalent amount of calcium carbonate, in which case the process is that of metasomatism, fully considered on pages 640–646.

The quantity of calcite and dolomite deposited between the grains of sediments, the vacuoles of igneous rocks, the openings of fissility, joints, and faults, while very great, is vastly less than that of quartz.

Siderite.—The iron in solution may be partly or largely precipitated in the form of siderite, ankerite, or ferrodolomite. These compounds all form somewhat extensively in the minor interstices in rocks, and occasionally they may form veins of such magnitude as to be worked as iron ore.

SILICATES.

The silicates which are most abundantly precipitated as cements are hydrous, but anhydrous silicates are also deposited. The important cementing silicates include, in order of abundance, the (1) zeolites and prehnite, (2) chlorites, (3) epidotes, (4) serpentine and talc. The zeolites and prehnite are sodium-aluminum silicates, calcium-aluminum silicates, sodium-calcium aluminum silicates, and potassium-calcium silicates. The chlorites are magnesium-aluminum silicates when pure, but ordinarily the magnesium is partly replaced by iron. The epidotes comprise zoisite (calcium-aluminum silicate) and epidote (calcium-aluminum-iron silicate). Serpentine and talc are magnesium silicates. As to the degree of hydration, the minerals may be divided into three classes: The zeolites and prehnite, the chlorites and serpentine, and epidote and talc. The bases of all of the above compounds are those which abundantly enter into the solutions. Hydration, as already shown, is one of the most important of the chemical processes which result in the liberation of heat. Probably the dominant factor in the precipitation of these hydrous compounds is the chemical law obtaining in the zone of katamorphism that, other things being equal, those compounds form by which the greatest amount of heat is developed and liberated.

The anhydrous silicates which are somewhat abundantly deposited in the belt of cementation are feldspar, hornblende, and mica, the order given being that of relative abundance. These materials may be deposited as independent constituents in the interstices of the rocks, and they may also

be deposited in optical orientation upon nuclei of like minerals. Feldspar enlargements have been found in many arkoses. Perhaps the best known instance is that of the Keweenawan sandstone of Lake Superior, the cementation of which is mainly accomplished by the deposition of feldspar upon worn grains of that mineral.[a] The grains are of different kinds of feldspar, orthoclase, and various plagioclases. The material deposited in each case is in optical continuity with the old material, even to the extension of the twinning lamellæ. (See fig. 14.) An excellent instance of the enlargement of hornblende is that of the hornblende crystals of the volcanic tuffs of Kekekabic Lake, in northeastern Minnesota.[b] The relations of the cores and additions of hornblende are identical with those of the feldspars, even to the extension of the twinning lamellæ. (See fig. 15.)

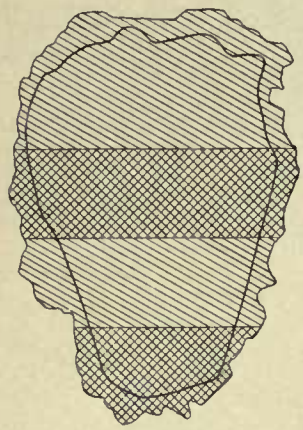


FIG. 14.—Enlargement of feldspar fragment.

The enlargement of feldspar and hornblende furnish the best illustrations known of the principle so strongly emphasized on pages 120–122, that mineral nuclei already present are able to abstract from solutions materials like themselves, and thus control the combinations of the elements when precipitated. In this principle probably lies the partial answer to the question why, in the cases cited of feldspar and hornblende enlargements, the material was not deposited between the grains as hydrous minerals. The formation of hydrous compounds would have developed more heat, but the power of the nuclei of old minerals to control the precipitation appears to more than have overbalanced the chemical law that in the belt of cementation reactions commonly take place which liberate the greatest amount of heat. But another factor which frequently enters into the precipitation of such anhydrous minerals as feldspar, hornblende, and mica is the abundance and the proper proportions in the solutions of the elements out of which they can be made. Rocks in which feldspar, hornblende, etc.,

FIG. 15.—Enlargement of hornblende fragment.

[a] Van Hise, C. R., Enlargement of feldspar fragments in certain Keweenawan sandstones: Bull. U. S. Geol. Survey No. 8, 1884, pt. 2, pp. 44–47.

[b] Van Hise, C. R., Enlargements of hornblende fragments: Am. Jour. Sci., 3d ser., vol. 30, 1885, pp. 231–235.

are deposited usually contain these same minerals in abundance, and in many cases the formations extend to the surface. The materials for the solutions may have been derived from the same minerals in the belt of weathering, or from a part of the belt of cementation above the places of deposition in case the waters are descending, and below the places of deposition in case the waters are ascending.

SULPHIDES.

The only important sulphide cement is that of iron. Iron is somewhat extensively thrown down as pyrite or marcasite. This may be precipitated by means of hydrosulphuric acid; it may be produced by the reduction of iron sulphate by means of organic reducing agents in the solutions or the rocks. These and other methods of precipitating sulphides are fully considered on pages 1108–1118. The quantitative importance of the cementing sulphides in the belt of cementation, from a geological point of view, is small, but from the point of view of ore deposits they are of the greatest consequence. (See pp. 1104–1105.)

DISTRIBUTION OF ELEMENTS IN CEMENTING MINERALS.

From the foregoing it appears that the elements added to the solutions from the belt of weathering and from the belt of cementation itself are distributed between the various minerals as follows:

The sodium passes into the silicates as zeolites, and may produce any one of the following sodium-bearing minerals of this group: Thomsonite, hydronephelite, natrolite, mesolite, gmelinite, analcite, phillipsite. The potassium passes into silicates as zeolite, being a constituent of apophyllite. The calcium passes into the carbonates and silicates. As a carbonate it is a constituent of calcite, dolomite, ankerite, and parankerite. As a silicate it enters into the zeolites and epidotes. The zeolites containing calcium are thomsonite, mesolite, scolecite, apophyllite, stilbite, phillipsite, gismondite, chabazite, and laumontite. Both epidote proper and zoisite contain calcium. The magnesium may enter into carbonates or silicates. As a carbonate it is a constituent of dolomite, ankerite, and parankerite. As a silicate it is a constituent of all the chlorites, of serpentine, and of talc. The iron may pass into oxide, carbonate, silicate, or sulphide. As an oxide it is a constituent of magnetite, hematite, and limonite. As a carbonate it is a constituent of ankerite, parankerite, and siderite. As a silicate it is a constituent of epidote and chlorite. As a sulphide it is a constituent of

pyrite and marcasite. The alumina passes into the hydroxides and silicates. As a hydroxide it is a constituent of diaspore and gibbsite. As a silicate it is a constituent of all the zeolites except apophyllite, of all the chlorites, and of the epidotes.

The carbon of carbonic acid enters as a constituent of the carbonates above mentioned. The silicon of silicic acid enters into quartz, opal, and the silicates above mentioned. The sulphur of hydrosulphuric acid enters as a constituent of the sulphides.

DISTRIBUTION OF CEMENTING MINERALS.

It is very noteworthy that the cementing minerals have a strong tendency to be like the compounds which are cemented. Thus the sands are transformed to sandstones and finally to quartzites by siliceous cement. Where nearly pure limestones and dolomites have been fractured, the dominant cementing minerals are calcite and dolomite. If, however, the limestone be a very cherty one, the cementing material may be largely chert. Where the porous rocks are largely silicates, as in the case of the amygdaloids, the cementing materials are mainly silicates, including the zeolites, epidotes, chlorites, etc., but also with these are usually associated important amounts of quartz and carbonates, one being correlative with the other; for carbonation of the silicates, forming carbonates, liberates silicic acid, which may separate as quartz.

These phenomena are beautifully illustrated by the amygdaloids of the Keweenawan series described by Pumpelly[a] and Irving,[b] and by the Crystal Falls volcanics described by Clements.[c]

In many cases not only are the silicates cemented by silicates, but the cementing minerals are like the dominant minerals cemented. For instance, the feldspathic sandstones may be cemented by feldspar, as in the case of the Keweenawan sandstones of Eagle Harbor.[d] Where hornblende is abundant the cementing material may be largely hornblende, as in the case of the Cacaquabic tuffs of northeastern Minnesota.

---

[a] Pumpelly, Raphael, Metasomatic development of the copper-bearing rocks of Lake Superior: Am. Acad. Arts and Sci., vol. 13, 1878, pp. 253–309.

[b] Irving, R. D., The copper-bearing rocks of Lake Superior: Mon. U. S. Geol. Survey, vol. 5, 1883, pp. 87–91, 134–139.

[c] Clements, J. Morgan, and Smyth, H. L., The Crystal Falls iron-bearing district of Michigan: Mon. U. S. Geol. Survey, vol. 36, 1899, pp. 73–154.

[d] Van Hise, cit., Bull. 8.

CAUSES OF CEMENTATION.

It has already been explained (see p. 156) that the amount of ground water which reaches the surface by springs and by seepage for a given period is approximately equal to the amount which is added to the sea of ground water. It is well known that all issuing waters contain material in solution; and it has been shown that the amount of such material may be greater than that which the solutions contained when they entered the belt of cementation. Notwithstanding the foregoing conclusion, it is an undeniable fact, as fully shown in the previous pages, that cementation is the rule for the part of the zone of fracture below the level of ground water. If more material be dissolved in this belt than is deposited by the circulating waters, what is the explanation of the apparently contradictory fact of deposition to the extent of complete cementation?

Before attempting to answer this question, it is advisable to recall the amount of openings which may be present in the belt of cementation. It has been shown that the coarse mechanical sediments frequently have an original average pore space as great as one-third; that in the thinly bedded lavas this amount is often equaled, and that the openings produced by mechanical action are great. It follows, as already clearly shown, that the amount of deposited cementing material is vast. Therefore we must not only furnish a cause which will result in the deposition of material in the pore spaces; but we must show that the causes assigned are quantitatively adequate to perform the great work.

In this connection it is well to restate the principles of precipitation worked out on pages 113–123. Mentioned in order of probable importance, precipitation is due (1) to the mingling of solutions from different sources, (2) to reactions between the solutions and the wall rocks, (3) to decrease in temperature, and (4) to decrease in pressure. The compounds are precipitated from the solutions in proportion as they are relatively insoluble and in proportion as they are abundant.

The law of chemistry that when compounds of different kinds come together substances form (if possible) which are insoluble in the liquids present, explains the importance of the first and second causes of precipitation. It has been shown that decrease in temperature is also very important, and that probably the importance of this factor in connection with decrease

of pressure has not been sufficiently appreciated. The experimental work of Barus[a] shows that at temperatures above 185° C. water and soft glass are miscible in all proportions. Further, it is held that water and rock are miscible in all proportions at proper temperatures and pressures. (See p. 723.) These conclusions throw new light upon the importance of the third and fourth causes of precipitation. If these conclusions as to the miscibility of water and rock be true, at the high temperatures and pressures which prevail in the deep seated circulation the water must be very rich in mineral content. It is clear that ascending waters which continuously fall in temperature and pressure must throw down great quantities of this material before they reach the surface. It is notable that large channels are most favorably situated with reference to all of these causes of precipitation, for in the large channels mingling of solutions is most likely to take place, along them reactions with the wall rock are important, and in them solutions are most likely to be ascending. (See pp. 582–584.) Therefore all the causes for precipitation combine to explain the great amount of material deposited in the large openings.

While all of these statements are undoubtedly true, in view of the fact already pointed out, that waters issuing from the belt of cementation may contain more material in solution than those entering that belt, none of them, nor their combinations, explain the general cementation in large and small openings alike. Before we can satisfactorily assign causes for general cementation it is necessary also to recall the cementing minerals and to indicate their relative importance. Of the substances deposited in the belt of cementation quartz is undoubtedly the one which dominates over all others. The one great process in the belt of cementation is silicification. Of very great importance is the deposition of the silicates and carbonates. Both of these classes of minerals are deposited on a great scale, but which of these is quantitatively the more important it is hard to say. It has been noted that of the various silicates deposited the important ones are the zeolites, the chlorites, the serpentines and talcs, and the epidotes. The deposition of oxide of iron, as hematite, limonite, etc., and of aluminum, as gibbsite and diaspore, is rather important, but quantitatively very subordinate to that of the classes of minerals already mentioned.

---

[a] Barus, C., Hot water and soft glass in their thermo-dynamic relations: Am. Jour. Sci., 4th ser., vol. 6, 1898, p. 270; and vol. 9, 1900, pp. 167–168.

We are now prepared to suggest causes which may combine to explain the apparently contradictory facts that a vast amount of openings in the belt of cementation is cemented and that emerging waters may contain more material in solution than entering waters; or that, of the two processes of deposition and solution, the latter is the preponderant one.

EXPANSION REACTIONS.

The first cause which will be given for cementation—and I believe the one of greatest importance—is that of expansion reactions. It has been explained (p. 603) that the chief reactions of the belt of cementation are oxidation, carbonation, and hydration, and that of these three the latter is of greatest consequence. Further, it has been seen that, provided all of the compounds formed remain as solids, the average volume increase in consequence of these reactions varies from 15 to 50 per cent or more. So far as these expansion reactions take place—and they undoubtedly occur on a most extensive scale—they tend to fill the openings, and thus cement and consolidate the rocks.

In the following section it is explained that the process of metasomatism, or change of the minerals within the body of the rocks, has taken place upon a vast scale in the belt of cementation. Indeed, in extensive ancient formations, especially in rocks of a porous character, it has frequently happened that, with the possible exception of quartz, scarcely a vestige of any original mineral remains. Many of the rocks, especially the igneous rocks, are largely or almost wholly composed of silicates. Even in the acid rocks the amount of quartz and other compounds, aside from the silicates, together is rarely as great as 50 per cent, leaving 50 per cent or more of silicates.

We shall now consider the expansion due to alteration of a rock which contains 50 per cent of silicates. If we suppose the silicates to be completely altered by the processes of oxidation, carbonation, and hydration, and that in these processes the expansion is 25 per cent—which is less rather than more than the average amount—if all of the materials were deposited the resultant expansion would be sufficient to furnish material to fill pore spaces to the amount of 12½ per cent of the total original solids of the rock. Therefore, in the case of an igneous rock of exceptional acidity and exceptional porosity, the expansion reactions would be adequate to entirely fill the openings of a rather porous rock. But it may be said that many of the

rocks, especially the lavas, contain more pore space than 10 or 12 per cent. This is especially likely to be true of the basic igneous rocks, of which the basalts may be taken as illustrative. But in basalt there is ordinarily no quartz. Practically the entire mass of the rock is composed of silicates, and the complete alteration of these compounds would furnish a sufficient amount of material, supposing the oxidation, carbonation, and hydration to produce an expansion of volume of 25 per cent, and all the compounds formed remain in situ, to fill a pore space of one-fifth the volume of the rock.

As an illustration of the very considerable amount of enlargement in volume by metasomatism in the belt of cementation a specific case may be given. For this purpose we may take a rock of intermediate composition. The amphibole-gabbro of Beaver Creek, Big Trees quadrangle, California, the mineralogical composition of which has been determined by Cross, Iddings, Pirsson, and Washington, will serve the purpose.[a] Columns (1) to (3) are taken from these authors:

Table showing relative volumes of original and altered rocks in belt of cementation.

(1) Mineral.	(2) Formula.	(3) Per cent.	(4) Volume ratio.	(5) Volume of resultant products.
Orthoclase	$K_2Al_2Si_6O_{16}$	1.11	0.8743	0.9705
Albite	$Na_2Al_2Si_6O_{16}$	23.06	1.2082	27.8611
Anorthite	$CaAl_2Si_2O_8$	43.92	1.3465	59.1383
Diopside	$CaMgFeSi_3O_9$	13.10	1.2788	16.7523
Hypersthene	$MgFeSi_2O_6$	3.92	1.1284	4.4233
Olivine	$Mg_2Fe_2Si_2O_8$	7.75	1.1519	8.9272
Magnetite	Fe_3O_4	2.55	1.0000	2.55
Ilmenite	$FeTiO_3$	1.67	1.0000	1.67
Apatite	$Ca_3P_2O_8$	1.55	1.0000	1.55
Pyrite	FeS_2	.20	1.0000	.20
Undetermined		1.37	1.0000	1.37
Total		100.20		125.4127

Supposing that the orthoclase by hydration and carbonation passes into kaolin and quartz, the decrease in volume is 12.57 per cent (p. 389). Supposing that the albite passes into analcite and quartz by simple hydration,

[a] Cross, Whitman, Iddings, J. P., Pirsson, L. V., and Washington, H. S., Quantitative classification of igneous rocks, Univ. of Chicago press, 1903, p. 199.

the increase in volume is 20.82 per cent (p. 375). Supposing that the anorthite by hydration passes into thomsonite, a zeolite with only a moderate amount of water, the increase in volume is 34.65 per cent (p. 376). Supposing that the diopside by carbonation, hydration, and oxidation passes into talc, quartz, magnetite, and calcite, the increase in volume is 27.88 per cent (see sahlite, p. 391). Supposing that the hypersthene by hydration and oxidation passes into talc, magnetite, and quartz, the increase in volume is 12.84 per cent (p. 385). Supposing that the olivine by hydration and oxidation passes into serpentine, magnetite, and quartz, the increase in volume is 15.19 per cent (p. 388). Since the percentages of the other constituents are small, they will be supposed to remain unaltered. In the above table, column (4) is the volume ratio and (5) the volume of resultant products.

It thus appears that the supposed reactions of hydration, carbonation, and oxidation of the amphibole gabbro result in an increase of volume of 25.21 per cent. It is to be noted also that the calculation is made upon a conservative basis. It might be supposed, for instance, that the anorthite, the most abundant mineral in the rock, passed into gismondite, which would increase its volume by 52.76 per cent rather than 34.65 per cent. Also, if the conditions were very favorable for oxidation the iron would pass to hematite and perhaps to limonite. If all these suppositions were made in favor of getting the maximum volume, this would make the volume increase considerably greater than calculated.

While the scoriaceous upper parts of lava beds may contain a pore space greater than 20 per cent, such a proportion of openings is comparatively rare for any considerable thickness of lava beds. It is well known that the amygdules of amygdaloids are ordinarily filled with quartz, with the zeolites, with chlorites, with epidotes, serpentine, and other hydrous silicates, and with carbonates; in other words, with the minerals mentioned on pages 621–627 as especially likely to be formed in the belt of cementation. That from the anhydrous silicates, hydrous silicates should form and fill the openings is to be expected. That the bases should unite with carbon dioxide is natural. But what is the source of the quartz? So far as carbonation of the silicates has taken place—and the presence of plentiful carbonates shows that this is an important reaction—silica, probably mainly in the form of colloidal silicic acid, is liberated. The precipitation of this

silica from the solutions forms the abundant chalcedony and quartz of the amygdules.

It therefore appears probable that, in the alteration in the belt of cementation of the porous rocks containing abundant silicates, expansion reactions characteristic of the belt of cementation may be entirely adequate not only to account for the filling of the openings, but possibly to furnish additional material to the ground solutions.

CONTRIBUTIONS FROM IGNEOUS ROCKS.

Expansion reactions, however, are not the only cause of cementation. In a subsequent section upon igneous rocks it is seen that injections locally produce profound metamorphic effects. It is there explained that the chief of these is the increased action of solutions due to the heat of the magma. But, as is well known, magma when solidifying gives off water. This water is sure to be very rich indeed in mineral content. The material thus contributed to the ground water solutions is certainly a source of material for cementation. This source is of importance, for volcanism is a widespread geological process. So far as material of this origin is available it explains the cementation of rocks notwithstanding the probability that solutions emerging from the belt of cementation contain more material than when entering this belt.

SELECTIVE PRECIPITATION.

But it is clear that the explanation thus far offered by no means fully covers the matter of cementation for all rocks. Indeed, it does not fully include the most important of the cases of cementation. It has been seen that the dominant cement of the belt of cementation is quartz. In many instances (see pp. 622, 865–866) the transformation of the great sand formations to sandstones and quartzites is wholly, or almost wholly, accomplished by the deposition of quartz. Probably 90 per cent or more of the fractures of rocks produced by deformation, such as joints, faults, bedding partings, etc., are cemented by quartz. The cementation by silicates, carbonates, etc., may be fully accounted for by the expansion reactions above given; but what is the source of the great quantity of silica for silicification? In order to answer this question we need to recall that the most distinctive process of the belt of weathering is carbonation; that there, by the process of carbonation of the silicates on a vast scale, colloidal silicic acid is set

free. This material is taken into solution by the descending waters and transmitted to the belt of cementation. As already pointed out, by the processes of denudation and downward migration of the belt of weathering, an abundant increment of silicic acid is ever contributed to the belt of cementation. If this material could be there deposited, this would account for the very general cementation by quartz. It has been seen that the silica largely separates from silicates as colloidal silicic acid. This compound is unstable, and tends to slowly decompose into water and silica. During the long and very slow journey of the water in the belt of cementation there is ample time for this process. It is likely that the principle that insoluble products are apt to be precipitated has a bearing at this point. Quartz is an extremely insoluble compound, and therefore tends to separate from the solutions bearing colloidal silicic acid. In the precipitation of the silica from the solutions the previous almost universal presence of quartz is also of great importance; for it has been shown (pp. 120–122) that the presence of a mineral of a certain kind favors the abstraction of like material from a solution and the addition of that material to the nuclei. Hence a large part of the most abundant substance contributed by the solutions from the belt of weathering is precipitated in the belt of cementation. As already pointed out, an additional supply of silica is furnished by the carbonation of the silicates within the belt of cementation. Finally, silica is furnished by emanations from intrusive rocks. Thus is explained the universal dominance of quartz as a gangue and cementing material, and the formation of great masses of sandstones and quartzites by this cementation process, as fully explained (pp. 864–868).

It is highly probable that the solutions are partly or fully compensated for the silica abstracted by the addition of calcium, magnesium, sodium, potassium, iron, etc., obtained by alteration of the minerals within the belt of cementation. It has been noted (pp. 609–610) that carbon dioxide is added to the belt of cementation in four ways. This carbonic acid unites with bases, producing carbonates. Further, it has been explained (pp. 624–625) that carbonates are very important compounds added to the belt of cementation. Thus the solutions of the belt of cementation have two sources of these compounds. It is therefore to be expected that undergound solutions which issue at the surface and in springs would bear as their most abundant compounds the carbonates of the alkalies, alkaline earths, and iron,

and with this expectation analyses of waters of springs fully accord. With the carbonates are also salts of other acids, such as hydrochloric, hydrosulphuric, and others, and also various salts of other subordinate metals.

From the foregoing it appears that during the circulation of water in the belt of cementation the processes of precipitation and solution are selective. Quartz and the hydrous silicates are the dominant precipitates. Carbonates of the alkalies and alkaline earths are the dominant salts which come to the surface. The above precipitations and solutions are precisely what should be anticipated from the laws of chemical precipitation given (pp. 113–123). The compounds which, on the average, are thrown down to the greatest extent are those which are least soluble and most abundant. The compounds which are retained in solution to the greatest extent are those which are most soluble and least abundant. However, of the more soluble and less abundant compounds a portion is precipitated. The conditions under which we should expect partial precipitation of these compounds are those of lessening temperature and pressure. These are the conditions of the ascending columns of water. It has already been seen that the ascending columns are likely to be the main water channels. Hence is explained the precipitation of the comparatively soluble carbonates of the alkaline earths and other minerals which form in the trunk channels.

By these various processes the larger openings are filled with deposits, some of which contain a sufficient quantity of valuable minerals to constitute ores. But where one large opening contains valuable minerals in sufficient quantity to be of service to man, millions are filled with quartz, hydrous silicates, calcite, dolomite, and other gangue minerals. It thus appears that the deposition of much of the ores is but a special phase of a general geological process of great consequence. This idea will be fully developed in Chapter XII.

DIFFUSION.

Other factors besides those already considered enter into the cementation of openings. Of these, diffusion is important. Before considering the influence of diffusion, it is necessary to recall some of the points already developed. After the water enters the belt of cementation it first has a downward movement, and usually later an upward movement.

Superimposed upon these vertical movements are lateral movements. During the downward course under normal conditions the temperature and the pressure steadily increase; during the upward course they steadily decrease. But there are irregular variations in temperature and pressure due to orogenic movements and to igneous intrusions. Increase of temperature and pressure increases the capacity of water to hold material in solution. The amount of material required to produce saturation is therefore exceedingly variable for different portions of the underground circulation. Equilibrium in the solutions extending between two places depends not upon the absolute quantity of material contained, but upon the relative approach to saturation at the various intermediate points. Material migrates by diffusion from places where the approach to saturation is nearest to places where it is less near, and this might be from a cool dilute solution to a warmer stronger solution. The conditions of equilibrium are therefore not those of uniform concentration, or in many cases even approximately so, for often the temperature and the pressure are different in horizontal columns from those in vertical columns, and vary greatly in vertical columns if they are of great altitude. Low temperatures and pressures obtain near the surface, and high temperatures and pressures obtain at depth. Consequently as depth increases more material may be held in solution before reaching a state of saturation; and because of this the conditions of equilibrium are those of greater concentration in the lower than in the upper parts of the columns. Moreover, the experimental work of Barus,[a] showing the wonderful dissolving power of water on glass at high temperatures and pressures, but still at temperatures which obtain in the lower part of the zone of fracture, shows that the differences in the amount of material held in solution may be very great—may, indeed, vary by ratios as great as 1 : 100 or 1 : 1,000.

From the foregoing it follows that if there were uniform concentration, with variable temperatures and pressures in the underground solutions, the material would diffuse from high levels to low levels and thus produce equilibrium. Where the currents are moving downward, but with decreasing slowness on account of the lateral movement of the water, which continually carries a part off to one side (see pp. 572–576), the lower

[a] Barus, Carl, The compressibility of hot water and its solvent action on glass: Am. Jour. Sci., 3d ser., vol. 41, 1891, pp. 110–116.

part of the column, because of its contact with the rocks for a greater time, would be more likely to be near the point of saturation than the higher parts; and thus there is a tendency for upward diffusion against the current. Diffusion is so slow that this movement might be thought to be of so little consequence as to be negligible; but it has been seen that the average downward movement of water in the belt of cementation is exceedingly slow, the rate of movement frequently not being more than a meter per annum. Therefore it is rather probable that upward diffusion against the downward-moving currents is a matter of consequence in maintaining the approximate equilibrium of the underground solutions, and therefore in promoting continuous and uniform precipitation throughout the belt.

During the upward movements which are characteristic of the later parts of the journey of the water currents diffusion may also work against the movement. This would be true if at the place where the upward movement began saturation had not been attained. At some higher point, as a result of the lessening temperature and pressure, saturation would be reached, and thus the coefficient of saturation would be higher. Hence there would be diffusion downward, or from places where there is less material in solution to places where there is more material in solution.

So far as the lateral movement of water is concerned, if variations in temperature and pressure be ignored, there is diffusion from areas of greater concentration to areas of less concentration. But the farther the water has gone, and the longer therefore it has been in contact with the rocks, the nearer are the solutions to saturation; hence there is a tendency for diffusion to take place against the currents. But where the temperature and the pressure are unequal, due to igneous rocks or orogenic movements or both, this condition of affairs may be reversed.

This factor of diffusion in connection with movements of the underground currents apparently explains some of the anomalous features of the belt of cementation. The downward movement may be presumed to be generally so slow that diffusion keeps the solutions approximately at equilibrium, and the process of cementation goes on subject to the laws of the expansion reactions and selective precipitation. But at places where the downward currents move so fast that diffusion does not maintain

equilibrium by movement of the dissolved material in a direction against the current, the descending waters continuously take material into solution; or, if not that, at least deposit little or no material; and thus a formation or an area in a formation below the level of ground water may not be cemented or indurated. In this manner may be explained the streaky cementation and induration of sandstones and quartzites, and very frequent preponderant solution below the level of ground water where there are strong descending currents (see p. 604). In places where the downward movement was slow and regular, cementation and induration are in an advanced stage or complete; while at places where there was rapid descending movement of the waters there was little deposition, and the material is but feebly or not at all cemented.

Besides the greater movements of diffusion connected with general currents of ground water, diffusion is unquestionably of great importance in the short movements of the ground water in the subcapillary openings between the single mineral particles or aggregates of mineral particles and between the adjacent capillary and supercapillary openings in which the main water currents travel. In the subcapillary openings, during the metasomatic processes, the water becomes saturated with material. Even if the water within the subcapillary openings itself does not move, the material in solution slowly migrates by diffusion toward the larger openings containing circulating waters, and vice versa. Therefore the materials of the small openings and those of the main water currents meet. The latter may carry not only recently acquired material, but material obtained long before, perhaps at great distances, or even from the belt of weathering above. As a result of this meeting selective precipitation takes place.

CONCLUSION.

From the foregoing pages I conclude that cementation is caused by the expansion reactions, by contributions from magmas, by selective precipitation, and by diffusion, and that these processes are adequate to explain the process, notwithstanding that the waters issuing from the belt of cementation contain large quantities of material in solution. In the actual precipitation in the openings of rocks these different factors work together, not separately.

The material precipitated is derived from three sources—that carried by the waters passing from the belt of weathering into the belt of cementation, that contributed by igneous emanations, and that which passes into solution within the belt of cementation. While at any one time the belt of weathering may not be of great thickness, as a consequence of denudation, there is steady addition of new material to this belt, and therefore a constant supply of material. If all of this material could be deposited in the belt of cementation it would undoubtedly be adequate for the work. The same is true of the material which passes into solution within the belt of cementation itself. But doubtless if the belt of cementation had only one of these sources, cementation would be very imperfect. It is only by the combination of the important sources of material that an adequate supply is obtained to furnish the issuing solutions the abundant materials which they carry and yet leave a sufficient residuum for cementation.

METASOMATISM.

DEFINITION.

Metasomatism may be defined as the process by which original minerals are partly or wholly altered into other minerals, or are replaced by other minerals, or are recrystallized with or without mineral changes, or one or more of these together. In the alteration of a mineral into other minerals, or in its replacement by other minerals, there may be addition or subtraction of certain constituents. As a result of the changes, the new rock may gain or lose variety in the minerals composing it. Either by the substitution of constituents, or by the loss of constituents, and therefore concentration of other constituents, a resultant rock may have a predominant mineral.

EXTENT OF PROCESS.

In rocks changed by metasomatism under mass-static conditions all stages of alteration may be seen, from comparatively fresh rocks, in which the changes are incipient in the minerals most readily alterable, to those rocks in which all alterable minerals have been transformed by metasomatism into others which are permanent under the prevailing conditions.

Throughout extensive areas important formations are so altered that no original mineral remains. That the recrystallization of great masses of

sedimentary and igneous rocks may go far toward or quite to completion under mass-static conditions is so well known that the fact need not here be emphasized. One of the best illustrative American localities is that of the Keweenawan series of the Lake Superior region. As shown by Pumpelly[a] and Irving,[b] the more porous lavas of this series have in many cases largely recrystallized. The less porous ones show extensive alterations. In various regions even great dense igneous masses have been profoundly affected or completely recrystallized throughout by metasomatic change.

However, as subsequently seen, the rocks which have recrystallized under mass-static conditions are easily discriminated from those which have been recrystallized under mass-mechanical conditions.

CONDITIONS FAVORABLE TO METASOMATISM.

Since the changes are produced mainly through the medium of water, the presence of a considerable amount of water, and especially conditions favorable to its circulation, are very favorable to metasomatic changes. It follows that in proportion as the rocks are porous metasomatism is likely to be rapid. But if there be sufficient time, in order to produce profound changes, there is no necessity for circulation of ground waters beyond that necessary to provide water for the development of the hydrated minerals which form in the belt of cementation so as to keep intact the minute amount of water in the small openings. If these conditions obtain, a very small amount of water may be the medium through which the rocks are completely altered and recrystallized. Even the subcapillary openings may be penetrated by solutions and the unstable minerals transformed throughout. But in dense rocks under mass-static conditions, where the spaces bearing water are all subcapillary, the changes are exceedingly slow. Even in the pre-Cambrian rocks, in the larger dense masses, such readily alterable minerals as nepheline and olivine are found. Olivine occurs extensively in the pre-Cambrian rocks of the Lake Superior region. Throughout extensive masses in this region the less alterable minerals, augite and basic feldspar, are apparently almost perfectly fresh. The

[a] Pumpelly, Raphael., Metasomatic development of the copper-bearing rocks of Lake Superior: Proc. Am. Acad. Arts and Sci., vol. 13, 1878, pp. 253-309.

[b] Irving, R. D., The copper-bearing rocks of Lake Superior: Mon. U. S. Geol. Survey, vol. 5, 1883, pp. 87-91.

small masses of dense rocks, especially those which are in the midst of porous rocks, are much more altered.

Porosity is also favorable to metasomatism because the necessary space is available for the expansion reactions of the belt of cementation without lifting the rocks. This necessity for more space is an important restraining factor in the alteration of the dense rocks.

In so far as the minerals are in a state of strain, this is favorable to solution and redeposition, and therefore, in proportion as this condition obtains, metasomatism is rapid. In so far as the mineral particles are finely divided, they furnish a large area for the attacking solutions, and therefore, in proportion as this condition obtains, metasomatism is rapid. Other things being equal, the higher the temperature the more rapid is metasomatism. Since normally the temperature increases 1° C. for 30 meters in depth, metasomatism is likely to be much more rapid in the middle and lower parts of the zone of fracture than in the higher parts. The process of metasomatism may be greatly promoted by increase of temperature due to intrusives, as explained on pages 648–649.

Metasomatism is rapid in proportion as the rocks are composed of readily alterable minerals. Of these leucite, nephelite, olivine, etc., are readily alterable; the pyroxenes, amphiboles, and micas occupy an intermediate position; and quartz and the acid feldspars are very slowly alterable under the conditions of the belt of cementation, although, as has been explained in a previous chapter (see p. 519), the feldspars are somewhat readily attacked in the belt of weathering.

Finally, the extent to which metasomatism has taken place is a direct function of the age of the rocks. The older a formation the more likely are the changes to be far-reaching.

MINERALS PRODUCED.

The dominant minerals produced by metasomatism are the same as the cementing minerals (see pp. 621–627), and this is what should be expected; for it is to be remembered that the solutions pass through the rocks slowly, and that the minerals deposited in the openings and those deposited in the body of the rock are alike the joint result of the reactions between the solutions and solids.

If this be so, it can not but follow that the minerals precipitated from the solutions in openings will be essentially the same as those produced by the changes within the mineral particles, although their relative proportions may be very different; for it is certain that the changes in the body of the rock are largely accomplished by solution and redeposition, although the material may be deposited very close to the place at which it was taken into solution.

GROWTH OF LARGE INDIVIDUALS WITH PRESERVATION OF TEXTURES.

One of the most distinctive features of metasomatism in the belt of cementation is the growth of large mineral individuals with the preservation or emphasis of original textures and structures.

The formation of large individuals is a result of the physical-chemical law explained on pages 74–76, under which large individuals form at the expense of smaller ones. In rocks altered by metasomatism in the belt of cementation the more than average growth of certain individuals may be recognized in the very unequal size of the mineral particles and in the enlargement of the old individuals. The general unevenness in the magnitude of mineral particles in rocks altered by metasomatism in the belt of cementation is so well known that the point need not be emphasized. While certain individuals may grow to much more than average magnitude, many others break up into very numerous smaller individuals of different kinds; for instance, the change of feldspar to quartz and mica. (See Pl. III, *A*.) The growth of large individuals at the expense of small ones explains the numerous interpenetrations of minerals in the recrystallized rocks. As a result of the disturbance of equilibrium from any cause, a change may take place. One mineral may grow. At the same time the adjacent mineral may be dissolved. The growth of one in many cases is apparently conditioned by the solution of the other. Cases of this are the growth of magnetite into quartz, and the secondary penetration of needles of actinolite and serpentine into quartz. (See fig. 16.)

FIG. 16.—Clastic quartz penetrated by serpentine. After Becker.

The enlargement of mineral particles has been described as occurring in quartz, feldspar, hornblende, augite, garnet, tourmaline, and other minerals, by Sorby,[a] Becke,[b] Irving,[c] myself,[d] Williams,[e] Hobbs,[f] Whittle,[g] and others. (See figs. 14 and 15.)

However profound the alterations of metasomatism by molecular mechanical action under mass-static conditions, the original textures and structures of the rock may not be greatly affected. It may be that all of the original minerals composing a rock are completely changed and yet the original igneous or other textures be perfectly preserved. The case is parallel to that of petrifaction of a wood in which no particle of the woody fiber remains and yet the textures of the original organic tissue are almost perfectly preserved. The modifications are mainly changes of substance, not changes of form. Thus all the textures characteristic of igneous rocks, such as granolitic, ophitic, porphyritic, etc., may be almost completely preserved in a rock which has altered throughout. This is illustrated by the dolerite dikes in the iron-bearing formation of the Penokee series of Michigan and Wisconsin. These dikes in the black impervious slates are little altered dolerites, but their continuations in the iron-bearing formation do not contain one vestige of any original mineral, but are ferruginous, hydrated, aluminum silicates, which in composition correspond very closely to kaolin.[h] Yet the texture in the altered rock and in the dolerite is the same.

Indeed, not only may there be no tendency to destroy textures and structures which were originally present, but there may be a tendency to

---

[a] Sorby, H. C., On the structure and origin of noncalcareous stratified rocks: Proc. Geol. Soc. London, 1880, p. 62.

[b] Becke, F., Eruptivgesteine aus der Gneissformation des niederösterreichischen Waldviertels: Tschermaks mineral. Mittheil., vol. 5, pt. 2, 1883.

[c] Irving, R. D., and Van Hise, C. R., Enlargement of quartz fragments and genesis of quartzites: Bull. U. S. Geol. Survey No. 8, pt. 1, 1884, pp. 11–43.

[d] Van Hise, C. R., Enlargements of feldspar fragments in certain Keweenawan sandstones: Bull. U. S. Geol. Survey No. 8, pt. 2, 1884, pp. 44–47. Van Hise, C. R., Note on the enlargement of hornblendes and augites in fragmental and eruptive rocks: Am. Jour. Sci., 3d ser., vol. 33, 1887, pp. 385–388.

[e] Williams, G. H., The greenstone-schist areas of the Menominee and Marquette regions of Michigan: Bull. U. S. Geol. Survey No. 62, 1890, p. 173.

[f] Hobbs, Wm. H., Phases in the metamorphism of the schists of the southern Berkshire: Bull. Geol. Soc. America, vol. 4, 1893, pp. 173–176.

[g] Whittle, C. L., Some dynamic and metasomatic phenomena in a metamorphic conglomerate in the Green Mountains: Bull. Geol. Soc. America, vol. 4, 1893, pp. 156–158.

[h] Irving, R. D., and Van Hise, C. R., The Penokee iron-bearing series of Michigan and Wisconsin: Mon. U. S. Geol. Survey, vol. 19, 1892, pp. 357, 358.

emphasize them. This emphasizing of old textures and structures results from the fact that solutions work along openings and surfaces of weakness. At any place in which water is present in more than the average amount, or is more than usually active, there may be greater than average solution and deposition, and thus emphasis of the old texture or structure. Common cases are the emphasis of perlitic cracks and bedding planes.

However, where large individuals alter to many small particles, or undergo a secondary enlargement with needle-like terminations, or are altered in various other ways, the original textures may become much less definite than they were originally, although the process of modification rarely goes so far as to obliterate original textures.

As a result of the preservation or emphasis of original textures and structures during metasomatism in the belt of cementation, it may happen that somewhat extensive changes in a rock are overlooked or ignored. Those who are most familiar with the recent little modified rocks are inclined to explain the phenomena they see in them as original. Those who have been working among the ancient and therefore more modified rocks are inclined to explain similar phenomena as the result of alteration. In each case the phenomena must be studied in the field and in the laboratory, taking into account all the evidence, in order to ascertain the actual truth; for it is certain that such phenomena as amphibole surrounding pyroxene cores and pegmatitic textures may be due to primary crystallization or to secondary alteration, and the appearance in the two cases be much the same, if not identical.

SEGREGATION OF INDIVIDUAL MINERALS.

Under exceptional conditions, by alteration or substitution or the two combined one mineral may very largely or wholly replace the minerals previously occupying a certain space. The space thus taken may vary from an insignificant amount to a considerable area for the entire thickness of a formation. In the latter case the process of metasomatism is often given a name dependent upon the mineral which replaces the other minerals, or that into which the other minerals alter. If, for instance, the segregating compound be silica, the process is called silicification; if it be serpentine, it is called serpentinization; if it be chlorite, it is called chloritization, etc.

Probably the most common of the various segregations is that of silica. This perhaps most frequently takes place in limestones, producing chert or quartz masses. According to Hinde,[a] silicification has extensively occurred at Spitzbergen and Axels Island, where formations once largely carbonates, aggregating 250 or more meters in thickness, are composed almost entirely of chert.

Cases of extensive serpentinization are those of the metamorphosed sandstones and igneous rocks in the Coast Range of California, described by Becker, where serpentine is said to replace quartz, feldspar, and apatite on an extensive scale.[b]

IGNEOUS WORK.

The igneous work of the belt of cementation is all comprised under "injection."

INJECTION.

By injection is meant the penetration of a rock by a molten magma. In the belt of cementation the injecting rocks make their way chiefly by following fractures, such as faults, joints, bedding planes, fissility planes, irregular fractures of brecciation, etc. The injected material therefore fills the larger crevices, such as those produced by faulting, jointing, bedding, fissility, or brecciation, and to some extent it may penetrate the interspaces between the individual grains—for instance, those of the ordinary sedimentary rocks. But it is probable that pure igneous injection between the mineral particles of the dense rocks does not usually penetrate a great distance from a continuous mass of the magma. Not only do the injecting masses utilize the openings already formed, but they force the walls apart and extend the openings, thus making possible intrusive masses of large size. The intrusive masses vary in size from great laccoliths many kilometers in extent and thousands of meters in thickness, through numerous great dikes or sills, many of which may be a hundred or more meters in thickness and many kilometers in extent, through dikes and sills of small size, to minute laminæ between the fissile leaves or to stringers between the grains.

---

[a] Hinde, G. J., On the chert and siliceous schists of the Permo-Carboniferous strata of Spitzbergen: Geol. Mag., new ser., dec. 3, vol. 5, 1888, pp. 241–251. Reviewed in Am. Jour. Sci., 3d ser., vol. 36, 1888, p. 73.

[b] Becker, G. F., Geology of the quicksilver deposits of the Pacific slope: Mon. U. S. Geol. Survey, vol. 13, 1888, pp. 122–125.

Injection by occupying the openings of the rocks indurates them. In these respects the process is similar in its results to cementation. The injection magma is a solution which crystallizes. This is a freezing of the solution. (See p. 113.) In cementation the solids crystallize from the solutions. It is believed, as will be seen (pp. 723–728), that the process of injection passes by gradation into cementation. The forms which injections take are often similar to those of the veins produced by cementation, and rock masses formed by either process may have the same relations to the previous structure of the rock.

Injecting materials comprise magmas of all kinds. Injections follow parallel and irregular fractures alike. Where the injections are in plane parallel openings, such as those of faults, joints, and fissility, the rock may take on a banded character. These bands may be large and wide apart, as is often true of injections along faults; smaller and closer together, as is frequent along joints; or very narrow and very close together, as is occasionally the case along planes of fissility. The banded rocks produced by injection may have an added complexity, due to the fact that many of the dikes follow one or more sets of fractures diagonal to the previous structure as well as parallel to it. Where the injections are in rocks with original irregular fractures, such as brecciation, this results in great complexity of structure.

The Sierra Nevada granite furnishes an admirable example of a rock which has been injected in a complicated manner. This granite is cut by several sets of intersecting joints. Many of these joints have been taken advantage of by the later injecting granite; and in the magnificent exposures in the region the dikes may be seen in parallel sets, intersecting other parallel sets of dikes. One of the localities in which the phenomena may be particularly well seen is the Yosemite Valley. Here there are at least six sets of intersecting joints. At some places two or three of these sets of joints have been taken advantage of by the entering material.

In some regions, after one set of fractures has been taken advantage of by injection material, succeeding orogenic movements have produced other sets of fractures, which have again been injected, and in some regions there may be found evidence of several distinct periods of fracturing and injections. Complicated injection is particularly likely to occur adjacent to great laccoliths within the zone of fracture.

Not only do igneous intrusions follow the various openings of rocks, such as those of joints, faults, fissility, brecciation, etc., and thus close them, but they produce a metamorphic effect upon the injected rocks. This contact effect may be confined to a centimeter or two adjacent to the intrusive or it may extend to a distance of several kilometers, depending upon many factors considered below. Furthermore, the contact effect, whether confined within narrow limits or affecting an extensive area, may be either slight or profound.

As already stated on page 488, the contact effect of the injecting upon the injected rock is known as the exomorphic effect, and that of the injected rock upon the injecting rock as the endomorphic effect. As has been fully explained on pages 489–494, the exomorphic effect is produced in two ways—by the direct contact action of the igneous rocks due to rise of temperature, and by indirect action through heated solutions. The exomorphism is ordinarily at a maximum immediately adjacent to the intrusive, and it decreases in amount, either rapidly or gradually, with distance from the intrusive. The change immediately adjacent to the injecting rock is often very marked. The rocks may be greatly indurated; the colors may be changed, etc.; and these physical changes are commonly accompanied by changes of chemical and mineral compositions.

The modifications of the intruded rocks immediately adjacent to the intrusive rocks are commonly attributed to direct contact action, but the change in chemical composition shows that solutions are also an important factor in the result, and therefore that there is indirect action. Indeed, in the belt of cementation the two are never independent, and it is impracticable to separate direct and indirect exomorphism and measure their quantitative importance. While this is true, it will be seen that contact metamorphism in the belt of cementation is only in small measure direct, and in very large measure indirect.

As fully explained on pages 490–494, in the belt of weathering the exomorphic effect is accomplished through gaseous solutions; in the belt of cementation the exomorphic effect is accomplished mainly through liquid solutions. In the latter belt, as in the belt of weathering, the solutions are modified in two ways—by the actual emission of water and associated materials from the igneous rocks to the solutions, and by the simple

heating of the solutions by the igneous rocks. In the belt of weathering the range of action of the gaseous solutions is somewhat limited. (See pp. 430–431.) In the belt of cementation the range of action of the liquid solutions may be far more extensive and the total result vastly greater. Indeed, I believe it would be difficult to overestimate this indirect effect.

The solutions are the great agents which permeate all the openings of the rocks, great and small, travel great distances from the source whence they derived their heat and dissolved materials, and in their journey everywhere alter the rocks.

To illustrate, the waters of hot springs, such as those of the Yellowstone Park, derive their heat from igneous rocks at considerable distances from the points where the waters issue, and throughout the journey the activity of these solutions is very greatly enhanced, and therefore exomorphism is greatly accelerated.

The amount of contact action and the distance to which it extends depend mainly upon (a) the porosity of the intruded rock, (b) the efficiency of the water circulation, (c) the composition of the intrusive and intruded rock, (d) the size of the intrusive masses, (e) the length of time of intrusion, (f) the temperature of the intrusive, and (g) the depth of the intrusion.

(a) A most important factor in the extent and amount of contact metamorphism is the porosity of the intruded rock. If the rock be nonporous the contact effect is usually limited to a somewhat narrow belt adjacent to the intrusive. If the intruded rock be broken by faults, joints, planes of fissility, and especially if the individual masses between the larger openings are porous, as in the case of sandstones, the contact effect for a given intrusive mass may extend many times farther and be many times more effective than in a nonporous rock.

Chemical change is greatly facilitated by the perviousness of the intruded rock. A porous rock, such as a sandstone or a fissile rock, has openings in which may be deposited great additions of materials different from the unmodified rock, and thus change its chemical composition. For instance, a quartzose sandstone may have large additions of feldspar or amphibole, as in the Wausau district of Wisconsin. On the other hand, an impervious rock, such as a mudstone or shale, may be but little changed, as the solutions can not readily penetrate this rock and carry with them

constituents of a different composition. Of course an impervious rock may be considerably changed in chemical composition immediately adjacent to the intrusive, but the change is not likely to extend far. (See c.)

(b) If circulating underground waters are in rapid motion in the intruded rock—and this of course depends, among other things, upon the porosity—the contact effect will extend widely and the alterations be great, for the rapidly moving percolating waters derive both heat and soluble material from the igneous rocks, or the heated rocks adjacent to them, and this material and the heat are carried far and therefore produce great effects.

(c) The amount of contact action depends upon the compositions of the intrusive and intruded rocks. The general law in this connection is that the exomorphism and endomorphism tend to make the rocks approach each other in chemical composition. Therefore the amount of change is likely to be great in proportion as the difference in composition of the intrusive and intruded rocks is great. If they be practically the same in chemical composition, the interchange of constituents through the solutions is not likely to greatly modify the composition of either. But if, on the other hand, the two rocks differ greatly in composition, each will be likely to gain constituents from the other and be modified in chemical and mineral composition. Each furnishes to the other materials in which it is deficient. Thus, if an intrusive rock in which feldspar and bisilicates are abundant, but in which quartz is absent, intrudes a rock rich in quartz, but one in which feldspar and bisilicates are absent, the intruded quartzose rock will be likely to gain feldspar and bisilicates, while the intrusive rock will be likely to gain silica, and may gain an amount sufficient to cause the silica to separate as quartz. An excellent example of the addition to the intruded rock from the intrusive is furnished by the adinoles and spilosites of the Crystal Falls district of Michigan described by Clements.[a] These metamorphosed slates contain very much more potassium than the average slate of the district. The igneous rock is rich in potassium and this element, therefore, must have been derived from that source.

In producing the above effects intrusive rocks are likely to cause important change in proportion as they are mobile and in proportion as they contain a large amount of occluded water. Indeed, to a certain extent

[a] Clements, J. Morgan, A contribution to the study of contact metamorphism: Am. Jour. Sci., 4th ser., vol 7, 1899, pp. 85–90.

these two factors are mutual; for the greater the amount of occluded water the greater the mobility of the magma. The greater the mobility the more extensive the intrusion is likely to be and the more minute the openings which may be entered. Further, magmas which contain a large amount of occluded water at the time of crystallization emit this water loaded with salts, and this material is added to the intruded rocks and increases the exomorphism.

(d) Other things being equal, the greater the mass of the intrusive the farther its effects are likely to extend and the more potent they are likely to be. While there is a tendency for the metamorphism to be proportional to the size of the intrusives, the small metamorphic effect upon the adjacent rocks which large intrusive masses, such as the great dikes or even the laccoliths, frequently show is astonishing. In many cases the intruded rocks seem to be scarcely modified at all by masses of the largest size in the belt of cementation. An excellent illustration of great intrusive masses with little or no apparent metamorphism is furnished by the extensive sills, from 10 to 100 or more meters thick, in the Animikie slates northwest of Lake Superior. But, as explained below, comparatively small masses of intrusive rocks may, for various reasons, result in profound modification.

(e) An important factor in the extent of metamorphism is the length of time through which flow continues along a certain opening. If magmatic flow continues long through an opening, the quantity of passing magma is great and the contact effect is likely to extend far and to be profound. This is a general consequence of the large amount of heat and emanations which may be furnished to the surrounding rocks and solutions by the long-continued intrusions. Long-continued flow of lava to higher levels or to the surface may take place through small openings, and a large intrusive mass may quickly form. Therefore a comparatively narrow igneous mass may be accompanied by profound contact action, because the changing mass furnishes to the intruded rock a continuous supply of heat and material to the solutions for a long time; while accompanying great masses of igneous rocks which simply occupied an area, comparatively little contact action may occur. The latter case is illustrated by the Henry Mountain laccoliths[a] and the great dolerite sills, some of them

[a] Gilbert, G. K., Report on the geology of the Henry Mountains: U. S. Geog. and Geol. Surv., Rocky Mt. Region, 1880, pp. 51–98.

hundreds of feet in thickness and many miles in extent, in the Animikie series of the north shore of Lake Superior.[a]

(f) The higher the temperature of the intrusive the greater the amount and extent of the contact effect. The temperatures of lavas as they reach the surface vary greatly, ranging from 700 to 1,100° C.[b] Other things being equal, it is evident that those magmas which have the higher temperatures are more effective in metamorphism, for two reasons. In the first place, they furnish a larger amount of heat to the surrounding rocks and solutions; and in the second place, they have greater mobility and therefore are more likely to extend far and enter minute openings.

(g) Other things being equal the greater the depth of the intrusion the greater the contact effect. One of the chief reasons for this is that rocks are very poor conductors of heat, and therefore the direct and indirect effect upon the intruded rocks continues for a longer time with a gradually broadening zone of action. Indeed, it is highly probable that the larger masses of the intrusive rocks in the middle and lower parts of the belt of cementation, of Tertiary age, have not yet cooled. The solutions of very greatly increased metamorphic efficiency on account of this heat have been at work for millions of years.

Finally, the pressure is much greater where the intrusives are deep seated, and this promotes metamorphism. This matter of the increase of the metamorphic power of intrusives with depth can not be too strongly emphasized. Indeed, in cases of widely extended and profound exomorphic effect the intrusives are almost invariably deep seated. As the depth of the intrusives increases, we gradually pass from the belt of cementation, which we are now considering, to the zone of anamorphism, to be considered in the following chapter. It will there be seen (pp. 711–736) that in that zone, where the intrusives are of still greater depths than in the belt of cementation, the contact effects are of the most profound character. But it can not be too strongly insisted upon that these effects are not mainly due to the direct heating effects of the intrusive rock, but to the indirect effect upon the solutions in heating them and furnishing materials to them. I repeat, the solutions are the important direct agents which produce far-reaching and profound metamorphism in the belt of cementation.

---

[a] Lawson, A. C., The laccolitic sills of the northwest coast of Lake Superior: Bull. Geol. and Nat. Hist. Surv., Minnesota, No. 8, 1893, pt. 2, pp. 24–48.

[b] Geikie, A., Textbook of geology: Macmillan & Co., London, 1893, pp. 225–226.

COMBINATIONS AND RELATIONS OF MECHANICAL WORK, CHEMICAL WORK, AND IGNEOUS WORK.

For the sake of clearness of analysis, each of the mechanical processes of consolidation—strain within the elastic limit, and fracturing; the chemical processes of cementation and metasomatism; and the igneous process of injection—has been treated separately. As a matter of fact, any one of the processes may be dominant in an individual case, as, for instance, the cementation of a sandstone to quartzite. Commonly, however, they do not occur independently in the rocks, but two or more take place simultaneously. The joint work of different combinations will be briefly considered in order to make clear the interaction of the processes.

The mechanical, chemical, and igneous processes often occur together, one frequently promoting the other. The chemical processes are promoted by the mechanical processes. Fracturing gives water a much larger surface of contact; it promotes water circulation; it allows easy injection. The mechanical processes induce a state of strain in the mineral particles where it does not fracture them. Therefore fracturing very notably promotes cementation, metasomatism, and injection. Indeed, in the belt of cementation, where the rocks are massive and originally contained no openings, cementation, metasomatism, and injection would take place with difficulty and slowly if it were not for mechanical action.

It has been explained that the processes of oxidation, carbonation, and hydration, characteristic of the belt of cementation, can take place only with expansion of volume. Where there are no openings available, in order that these reactions shall occur, it is necessary that much material shall be dissolved to compensate for this expansion; and in the massive rocks the water circulation is so slow that the material can be dissolved and transported from the belt of cementation only very slowly indeed. This, therefore, is the explanation of the small amount of alteration in the belt of cementation where the rocks are not porous and have not been fractured.

However, where the massive, originally nonporous rocks have been fractured, the fracturing increases the total volume of the rocks by the amount of the openings produced. Later the openings are closed by cementation, metasomatism, and injection, and thus there is absolute increase in the volume of the material. This increase has been estimated

by Shaler, as already noted (p. 127), to be 3 to 5 per cent of the superficial area at certain places along the New England coast,[a] and this corresponds to an increase in volume from 0.52 to 1.12 per cent. Where one set of openings which originally existed or has been produced by fracturing has been closed by cementation, metasomatism, and injection, a new set of ruptures may form, thus further increasing the volume of the rocks, and these openings may again be closed by cementation. Of course, in such rocks as were originally very porous—for instance, the sandstones and amygdaloids—the alterations of the belt of cementation may take place with no gross expansion of the volume of the rocks, the necessary spaces being found in the original openings.

The conditions favorable to cementation and metasomatism are usually the same; therefore the two processes naturally occur together. In some cases, such as cementation of a pure quartz sand, cementation may take place without marked metasomatism; but this is exceptional. Metasomatism is almost invariably accompanied by cementation, and usually where the former process is important the other is sure to be of consequence. Where injections occur it has been seen that, besides closing the openings, an extended and profound exomorphic effect is produced. Further, it has been seen that this is especially likely to be true when the exomorphism is indirect or the work of solutions. But the alterations accomplished by the solutions as an agent are cementation and metasomatism. Therefore, where injection is an important metamorphosing influence, cementation and metasomatism are exceedingly active and widely extended. The underground waters are heated. These heated waters dissolve a large amount of the material of the injected and injecting rock; they receive a further contribution furnished by the solutions emanating from the injected rock. Solutions thus enriched travel for a greater or less distance, but ultimately a portion of the material is deposited, thus cementing the rocks. Just as injection promotes cementation it promotes metasomatism, and for the same reasons. The solutions are heated and rich in mineral materials, and therefore the mineral particles present in the injected rock are modified. It follows from the foregoing that the chief indirect exomorphic effects are accomplished by cementation and metasomatism.

[a] Shaler, N. S., The crenitic hypothesis and mountain building: Science, vol. 11, 1888, p. 281.

Irving further points out[a] that, after an igneous rock has solidified, as it continues to cool it contracts, and therefore at the contact of the igneous rock with the intruded rocks openings are likely to be produced. Frequently the contraction openings are not confined to the contacts, but extend into both the injecting and the injected rock. Such openings, being within the intrusive rocks or near the contacts of the intrusive and intruded rocks, furnish trunk channels which are likely to receive solutions from both the injecting and the injected rocks. Thus are explained the very frequent trunk channels for circulation and vein formation within and adjacent to igneous rocks. The openings along the borders of igneous rocks and within them are of very great consequence in connection with ore deposits. (See p. 1116.)

Concluding, it is clear that while one or two of the processes of cementation, metasomatism, and injection may occur without the other one or two, it is rarely that one works alone. Of the processes, that which is most likely to occur without the others is cementation. Metasomatism rarely, if ever, takes place without cementation. Cementation and metasomatism may take place on an extensive scale without injection. Injection is invariably accompanied by cementation and metasomatism.

CHANGES OF CHEMICAL COMPOSITION.

The amount of change in the chemical composition of the rocks in the belt of cementation is likely to vary with the porosity. Where the rocks are dense, chemical analyses appear to show that the average composition of the rocks does not greatly change, except by oxidation, carbonation, and hydration. The oxygen and carbon dioxide are added directly or indirectly from the atmosphere, and the water from the hydrosphere. In the opening pages of Chapter II it has been explained that all chemical changes involve molecular mechanical action, even where the average chemical composition remains the same. There may be interchange on a great scale between the minerals within short distances (for instance, glasses may wholly devitrify), but in the dense rocks the migrations of material are ordinarily confined within somewhat narrow limits and the average change in chemical composition is not great.

---

[a] Irving, A., Chemical and physical studies in the metamorphism of rocks, Longmans, Green & Co., London, 1889, pp. 82–84.

In the porous rocks, such as sandstones, extrusive igneous rocks, especially the vesicular lavas and porous tuffs, and much fractured rocks, where there is comparatively rapid circulation of water, the migration of materials for considerable distances may be important. The addition or subtraction of material at any place may be large; for instance, simply filling the pore spaces may require the addition of 20 to 40 per cent of the volume of the rocks. (See pp. 569–570.) Also alterations extend through the minerals originally present. Therefore the chemical compositions of the rocks for extensive areas may be much changed. Excellent illustrations of the transportation of material for long distances and its replacement of other material, thus changing the composition of the rocks, are furnished by the segregation of individual minerals, described on pages 645–646. One of the best illustrations of extensive change in chemical composition is furnished by the silicification of limestone formations. (See pp. 646, 816–820.) Perhaps there is no more conclusive case of replacement than the very numerous instances of partial and complete substitution of copper for porphyry pebbles and bowlders, described by Pumpelly,[a] in the Calumet and Hecla conglomerate. Other illustrations of replacement are furnished by many of the ore deposits.

[a] Pumpelly, Raphael, The paragenesis and derivation of copper and its associates on Lake Superior: Am. Jour. Sci. for Sept., Oct., and Nov., 1871, vol. 2, pp. 188–198, 243–258, 347–355.

CHAPTER VIII.

THE ZONE OF ANAMORPHISM.

DEFINITION OF ZONE.

In Chapter IV the zone of anamorphism has been treated from a physical-chemical point of view. It is there shown that this is a zone in which there is great pressure in all directions, and that this is the dominant factor controlling the reactions, so that changes take place which diminish the volume of the rocks. The chemical law of energy is subordinate to the dominant physical demand of pressure for reactions which lessen the volume. Chemical reactions therefore take place with liberation or absorption of heat, as demanded by the pressure; but in large measure pressure demands that chemical reactions take place with absorption of heat, such as silication, dehydration, deoxidation.

It is the purpose of the present chapter to consider the zone of anamorphism from a geological point of view. The zone of anamorphism is bounded above by the belt of cementation of the zone of katamorphism. It has no assignable boundary below. The depth of the upper surface of the zone of anamorphism is very variable, depending upon many factors, among which the strength of the rocks and the speed of deformation are very important. It is not practicable to assign a minimum limit to this depth, but it is highly probable that in many cases the upper surface of this zone is not at greater depth than 1,000 to 2,000 meters, for rocks have been modified by the reactions characteristic of the zone which have apparently not been buried to a greater depth than this. By making assumptions so as to give a maximum depth for the belt of cementation, the upper surface of the zone of anamorphism is calculated to be at a depth not greater than 10,000 to 12,000 meters.[a] (See pp. 189–190.)

[a] See Van Hise, C. R., Principles of North American pre-Cambrian geology: Sixteenth Ann. Rept. U. S. Geol. Survey, pt. 1, 1896, p. 593.

It has been said that no lower limit can be given for the zone of anamorphism. The alterations certainly obey the physical laws of the zone of anamorphism to the depth at which observation is possible as a result of deformation and denudation. How the rocks behave at greater depths is only to be judged by inference. So far as one can foresee the action of the laws of energy, it appears highly probable that the reactions of the zone of anamorphism extend to a very great depth. But in this treatise the zone of anamorphism is restricted to the lower part of the lithosphere of which we have observational knowledge, and, following Powell, I apply to the unknown depth below it the term "centrosphere."

The zone of anamorphism differs in an important respect from that of katamorphism, in that the openings are in general those of subcapillary size. This follows from the fact that the pressure in all directions is greater than the crushing strength of the rocks, and if large openings could be supposed to exist they would be closed by the flowage of the rocks. While the general fact of the subcapillary size of the majority of the openings in the zone of anamorphism is beyond doubt, it can not be stated that somewhat larger openings do not exist. So far as there are openings which are filled with liquid that can not escape, the above reasoning does not apply, for the inclosed liquid successfully resists the closing of the cavities. By general reasoning one is not able to determine how large such liquid-filled openings are, but observation indicates that they are small, in general so small that they are observed only by the microscope, and in no cases known to me are they larger than capillary size.

One modification of the above statements should be made in reference to openings in the rocks in which the alterations are mainly those of the zone of anamorphism. During periods of very rapid deformation large fractures may extend much deeper than under ordinary conditions, for whether rupture takes place by major fractures or by flowage is largely dependent upon the speed of the movement. This principle can not be better illustrated than by the deformation of marble at the surface. Where a marble slab is rapidly deformed at the surface, it is ruptured. Where, however, a similar slab is laid horizontally, being supported only at the ends, so that gravity steadily tends to bend it, the slab bends very slowly with permanent set. This is illustrated in cemeteries by slabs long suspended in the manner described. Julien cites a number of instances of the bending of marble

slabs at the surface without rupture, the most notable being that of an upright marble slab, 3.35 meters long, 22.8 cm. wide, and 6.35 cm. thick, in one of the doors of the Alhambra, Spain, which, through the settling of the material of the wall, had attained a curvature of 76.2 mm.[a]

From these illustrations it appears that a strong force rapidly applied may deform a rock by fracture, whereas a very moderate force slowly applied may deform it by flowage. This principle probably has great geological significance in metamorphism. Where the deformation is very rapid the zone of fracture and the alterations of the zone of katamorphism may extend to great depth. Under such circumstances igneous injection and cementation may go on, but as soon as the earth movements cease, or lessen in speed, the openings are gradually closed by rock flowage under the laws of the zone of anamorphism. Thus a great zone or belt of rocks is alternately under conditions of the belt of cementation and under conditions of the zone of anamorphism, according as deformation is fast or slow. This subject will be further considered on subsequent pages, especially in the section on pegmatization. (See pp. 720–728.)

CONDITION OF WATER.

In considering the condition of water in the zone of anamorphism the temperature is of the utmost importance. It has been explained on page 566 that above a temperature of 365° C., the critical temperature of water, water can exist only as gas. Supposing the increment of increase of temperature with depth to be 1° C. for 30 meters, this temperature would be reached at a depth of 10,950 meters, even if the temperature be 0° C. at the surface. It has been explained that the upper surface of the zone of anamorphism is probably in most cases at a depth not greater than one-half of 10,950 meters. It therefore is clear that in the upper part of the zone of anamorphism the water may be in the form of heated liquid, not as water gas. Disregarding igneous rocks and orogenic movements, where the critical temperature is not reached, even if the water were at temperatures far above the boiling point at the surface, the water would be held in the form of liquid by the pressure, as fully explained on pages 566–569. In so far as the water is in the form of liquid, nothing further need be said

[a] Julien, A. A., The durability of building stones, etc.: Tenth Census of United States, 1880, vol. 10, 1884, pp. 366–367.

in reference to it, for the laws controlling its movements and metamorphic action are precisely the same as those governing the heated water of the belt of cementation. (See pp. 566–646.) But at depths greater than about 11,000 meters the water must be supposed to be gas. Moreover, in consequence of igneous intrusions and orogenic movements, the critical temperature is probably frequently attained over extensive areas at depths much less than this. Therefore it is highly probable that for much of the zone of anamorphism the water is in the form of gas, not liquid.

The general statement may be made that, for the greater part of the zone of anamorphism, water is in the form of water gas, but that for considerable portions of the upper part of the zone the water is in the form of liquid. Thus, in this matter the zone of anamorphism is in direct opposition to the zone of katamorphism, where the water is dominantly in the form of liquid and only exceptionally in the form of gas.

The probable action of water gas in the zone of anamorphism should be considered. What are the differences between the circulation and work of water in the form of liquid at high temperatures and under great pressures and the circulation and work of water gas at such temperatures and pressures? At the pressures existing in the zone of anamorphism it is certain that the gas would be dense. At the depth of 10,950 meters the pressure per square centimeter of a hydrostatic column of water to the surface would be 1,095 kilograms, or 1,060 atmospheres.

The density of water gas at atmospheric pressure and 100° C. is 0.0006 of the density of water at 4° C. Assuming, for purposes of calculation, that, under the temperatures and pressures given, water gas acts as a perfect gas, H. C. Wolff has calculated for me that at a pressure of 1,060 atmospheres and at the critical temperature of water (365°), the density of the gas would be 2.32 times the density of water at 4° C., a result almost certainly too great, but still indicating that the gas is very dense.

In a very dense gas the molecules attract one another,[a] and in so far as this is true the gas approaches a liquid. It is certain that superheated water at high temperature has a low viscosity and remarkable chemical power, as shown on pages 79–81, 105–110, 140–141. In so far as the water gas in the openings of the zone of anamorphism is less dense than the liquid

[a] Nernst, W., Theoretical chemistry, trans. by C. S. Palmer, Macmillan & Co., London, 1895, p. 185.

in the openings, this would reduce its chemical activity; but the fact that the viscosity of the gas is probably less and its temperature higher may render a small quantity of water in the form of gas as potent or even more potent in the transformation of rocks than a much larger amount as liquid.

QUANTITY OF WATER.

The quantity of water in the crystallized rocks of the zone of anamorphism is certainly small as compared with that in the belt of cementation. It has been explained that the openings of the zone are normally of subcapillary size, although some of them are as large as capillary openings. The quantity of water is therefore limited to the space which may be furnished by these openings, unless it be supposed that under the extraordinary pressures and high temperatures which prevail in this zone the water gas finds a place between the molecules of the crystallized minerals, and this hypothesis can not be proved. Ignoring this possibility, it is probable that the amount of free water in the forms of liquid and gas in the zone of anamorphism is in most cases less than 1 per cent.

CIRCULATION OF WATER.

Before the question as to the circulation of the water in the zone of anamorphism can be satisfactorily discussed, it is necessary to answer the question as to the probable sources of the water. The certain sources of water in the zone of anamorphism are (a) the water mechanically contained in the rocks at the time they passed into the zone, (b) water produced by dehydration of hydrous minerals, and (c) water from igneous intrusions.

(a) The sediments as originally formed commonly contain large quantities of water in their interstices. As explained on pages 124–127, this amount by volume is frequently 25 per cent or more. By deep burial the sediments pass into the zone of anamorphism. In most cases it is highly probable that before this takes place the larger portion of the original water has been lost as a consequence of consolidation and cementation. But it is not likely that all of the water is lost, and therefore the sedimentary rocks as they pass into the zone of anamorphism probably carry with them mechanically mingled water. As to the quantity of this water, no certain knowledge is available; but I suspect that in the majority of cases it is small, possibly less than 1 per cent. Doubtless the rocks of the centro-

sphere which pass into the lower part of the lithosphere also contain some mechanically mingled water, but it is rather probable that the amount is very small.

(b) It has been noted that dehydration is one of the most important reactions of the zone of anamorphism. Water is thus set free within the zone of anamorphism. Dehydration is therefore a certain source of water. It is explained elsewhere (pp. 742–744, 895–896) that in muds the combined water is about 8 per cent, in shales is only about 4 per cent, in slates about 3 per cent, and in schists about 1.50 per cent. The process of metamorphism by which a mud is transformed to a schist requires the squeezing out of least 6.5 per cent of water by weight. If the conclusion be true that in general in the zone of anamorphism the quantity of free water is less than 1 per cent, the process of dehydration is capable of producing more water than is present at any one time. Dehydration is therefore an important source of water. Indeed, water of hydration is probably a main reservoir of this essential agent for the recrystallization of the rocks in the zone of anamorphism.

(c) It will be explained under "Injection" that igneous intrusion is one of the important processes which modify the zone of anamorphism. It is well known that when a magma makes its way to the surface it may contain a considerable amount of occluded water. The amount of this water is greater in many cases than the amount ordinarily contained in the crystallized deep-seated equivalents of these magmas. If this be so, the process of crystallization of intruded magma in the zone of anamorphism may release water within the zone, and thus furnish another important source of this agent within the zone itself. How important this source of supply is, is more or less conjectural, but I suspect that it is important, as will be more fully explained under "Pegmatization." But it is necessary to say here that where there are great complex intrusive masses in the zone of anamorphism the central masses crystallize like igneous rocks. Often pegmatites and veins form peripherally to this central mass. In their crystallization water is believed to be a very important agent, and it is rather probable that this agent, or at least a large part of it, is that liberated during the crystallization of the large igneous masses.

In addition to the above sources of water, water may have passed from the belt of cementation downward into the zone of anamorphism, or from

the centrosphere upward into the zone of anamorphism. But it is probable, as will be seen below, that these are not important sources of water. I suspect that, on the average, the mechanical water and the water of dehydration are the main sources of water supply of the zone of anamorphism. My reason for this belief is that rocks which, containing large quantities of combined water, like the sediments or the porous lavas, are readily recrystallized in the zone of anamorphism, as fully explained on pages 741–748; whereas great masses of igneous rocks in which there is a deficiency of combined water are very frequently not recrystallized, but granulated. The fact that massive igneous rocks containing little combined water do not readily recrystallize is rather clear evidence that sufficient water to do this work is not driven downward from the belt of cementation, or upward from the centrosphere into the zone of anamorphism.

We are now prepared to consider the circulation of the water in the zone of anamorphism. It has been seen that the available openings are mainly those of subcapillary size. It is through these openings that the water must circulate, unless it be assumed that under the high pressures and temperatures obtaining in parts of the zone of anamorphism the water can make its way through the intermolecular spaces of the solid crystallized minerals. This has been held by some geologists. It has been pointed out that water is certainly occluded within magmas; but this is a very different thing from the existence of free water between the molecules of a crystallized substance. While the possibility of the transmission of water in this manner is not denied, it is a mere hypothesis; and therefore the only openings which we know to be available for water circulation are those of subcapillary size, with possibly a relatively few of capillary size between the mineral particles.

The movement of the water through these openings must be slow because of their subcapillary size. It has been explained on page 143 that in openings of this kind the attraction of the mineral particles extends from wall to wall, and the films are strictly adherent and therefore not free water at all. But as the temperature becomes high the viscosity of the water becomes much less, the molecular attraction between it and the rock is decreased, the adherent film is less fixed, and its mobility is therefore very greatly increased. Also, in so far as the temperature of the water exceeds its critical temperature, it is in the form of a gas; between a gas

and the rock particles molecular attraction is not so important as between rock particles and a liquid; therefore, so far as the water is gaseous, there are probably no strongly adherent films in the openings. The gas, as already explained, is very dense; gas is very mobile; therefore, so far as the water is in the form of gas, it would be likely to very effectively make its way from places of great pressure to places of less pressure. With a given amount of water per unit volume the water gas would move from places of higher temperature toward places of lower temperature, for with a given amount of gas occupying the same volume, the higher the temperature the higher the pressure.

As to what extent the water is in the form of liquid and to what extent it is in the form of gas we know so little that no attempt is made to discuss the movement of the two separately. The statement below is true for both aqueous solutions and gaseous solutions of the zone of anamorphism. Where the term water is used in the succeeding paragraphs there is no implication as to which state the compound is in.

Disregarding the possible transmission of water through the intermolecular openings, all of the subcapillary and capillary openings would be taken advantage of at every favorable opportunity, and favorable opportunities would be furnished at times of orogenic movement. In the zone of anamorphism during earth movements the mineral particles either are broken and move differentially with reference to one another, or else are recrystallized, or the two combined. In any case there is a constant readjustment of the rock material by which the positions of the minute openings are constantly changed. Where the movements are rapid, supercapillary openings temporarily extend downward from the belt of cementation. (See pp. 658–659.) During orogenic movement the pressures vary greatly from place to place; indeed, at the same place they vary from moment to moment. This results in very variable pressure upon the water solutions within short distances. Therefore, during orogenic movements, when the rock material itself is in motion, the water is in most active movement. The activity of the water in connection with deformation would be further likely to be promoted by the fact that locally the movements would raise the temperature above the critical point if it were not so already, and thus the water would be in the form of water gas, and hence have the high mobility of that form.

As to the direction of circulation for a given depth, it can be said that the movements would be from places of greater pressure and higher temperature to places of less pressure and lower temperature. It seems probable that the water would move laterally from places of intense orogenic movement to places of less strong orogenic movement. It seems probable that water would move away from places of igneous intrusions, because these produce high temperatures and pressures.

But the water movements of greatest geological interest are the vertical movements. Does water make its way downward from the belt of cementation or upward from the centrosphere into the zone of anamorphism?

It has been explained that the water at the upper part of the zone of anamorphism is under great pressure and at high temperature. It might be supposed, under these circumstances, that the water would make its way downward into the rocks below. This has been a favorite hypothesis of those who have explained the water contained in magmas issuing from volcanoes as of surface origin. The experimental work of Daubrée has been appealed to in support of this view. Daubrée showed that water gas at a temperature of 160° C. penetrated through a slab of fine-grained sandstone 2 centimeters thick, and produced a pressure upon the other side of 1.9 atmospheres (1,963.2 grains per sq. cm.).[a] However, it is to be remarked that an essential point in this experiment is that the amount and pressure of water gas are very much less upon the side of the rock to which the water makes its way than upon the other side, for to hold water as liquid at a temperature of 160° C. a pressure of about six atmospheres is required. If there were no water in the zone of anamorphism there is little doubt that the water would make its way from the belt of cementation into the zone of anamorphism until equilibrium were reached. The force tending to carry this water downward is that of gravity, and is equal to the pressure of a column of water from the bottom of the belt of cementation to the surface. But before we can assume that this pressure is sufficient to drive the water into the zone of anamorphism we must be certain that the pressure in that zone is not as great as or greater than in the lower part of the belt of cementation.

We have seen that water may be present in the zone of anamorphism from at least three sources. This water is under the high pressure of the

[a] Daubrée, A., Études Synthétiques de Géologie Expérimentale, pt. 1, Paris, 1879, pp. 236–241.

plastic rocks, and in large part above the critical temperature of water. It is a characteristic of the zone of anamorphism that the rocks are not sufficiently strong to sustain themselves, and that consequently no large and continuous openings are present; therefore the imprisoned water is not subject to the hydrostatic pressure of a column of water reaching to the surface only, as is that of the belt of cementation, but to the weight of the rock column to the surface, which is approximately 2.7 times as much as the pressure of an equivalent column of water. It has been seen that in much of the zone of anamorphism the water is above its critical temperature, and therefore that the enormous expansive force of this gas is tending to drive the water from the zone of anamorphism to the belt of cementation. In the experiment of Daubrée[a] the water gas traveled from a place of greater pressure to a place of less pressure. So far, therefore, as this experiment is applicable to the case under discussion it indicates that the water would be driven from the zone of anamorphism to the belt of cementation. From a consideration of physical principles, therefore, we conclude that water does not pass from the belt of cementation to the zone of anamorphism, but probably is driven by the superior pressure and the expansive force of the gas from the zone of anamorphism to the belt of cementation.

This conclusion, reached by physical reasoning, is fully confirmed by the facts of observation. It has already been pointed out that, in the zone of anamorphism, in the transformation of a shale to a schist the amount of combined water is reduced from 4 to 1.50 per cent. But the amount of free water in the zone of anamorphism is only a fraction of 1 per cent. This liberated water must have escaped either above or below. That the relative pressures in the zone of anamorphism and the belt of cementation are such as to make the movement upward has already been seen, and there can be little doubt that much or most of the water freed by dehydration goes in this direction. This seems to me highly probable from the fact that the amount of combined water in the recrystallized rocks lessens as the intensity of the metamorphism increases. Where the rocks have been metamorphosed under moderately deep-seated conditions, such minerals as chlorite may be found; where the metamorphism was deeper seated, biotite and muscovite, containing less water, are abundant; but where the metamorphism is most profound, and where apparently the pressure has

[a] Daubrée, cit., p. 236–241.

gone to the extreme recognized by observation, muscovite and biotite may be destroyed, with the production of such heavy anhydrous minerals as garnet, staurolite, etc. Therefore the water apparently does not make its way downward, or if it does it is water occluded between the solid molecules rather than water combined with them; but as already stated, there is no evidence that water can exist in important quantity in such positions. From the above facts, since the amount of water apparently decreases with the intensity of the metamorphism, or practically, disregarding local irregularities, with depth, and the freed water must escape somewhere, I conclude that the probable general movement of the water present or produced by dehydration and from magmas in the zone of anamorphism is upward into the belt of cementation.

This conclusion is confirmed by other facts in connection with metamorphism. It has been said, and will be fully explained, that silication of carbonates, forming silicates and releasing carbon dioxide, is one of the chief reactions of the zone of anamorphism.[a] In the rocks metamorphosed under deep-seated conditions inclusions of liquid and gaseous carbon dioxide in the cavities are very common. When formed all of the occluded carbon dioxide was probably a dense gas, because above its critical temperature. Under surface conditions, below critical temperature and with the high pressures of the gaseous portions, the carbon dioxide largely condenses to a liquid. It is a fact that waters rising from a deep-seated source almost invariably carry large quantities of carbon dioxide. It seems highly probable that much of the carbon dioxide brought up by the rising deep-seated waters is a portion of that carbon dioxide liberated by the process of silication of the carbonates. If this be true, it is further probable that the upward movement of the carbon dioxide was accompanied by water or water gas, for there is no reason why one should go up and the other down.

Therefore it seems to me that the principles of physics and the facts of observation both lead to the conclusion that, so far as the vertical circulation of water between the zone of anamorphism and the belt of cementation are concerned, the transfer is upward, from the former to the latter.

---

[a] See Le Conte, Joseph, Genesis of metalliferous veins: Am. Jour Sci., 3d ser., vol. 26, 1883, p. 9.

The next question of importance is the probable movement of water between the zone of anamorphism and the centrosphere. We know nothing as to the average comparative amount of water in the openings of the lower part of the zone of anamorphism and in the openings of the centrosphere below, nor do we know the pressures and temperatures to which the water is subjected. If the amount of water in the centrosphere be as great as it may be supposed to be from the quantity in the extrusive lavas, it is pressing upward toward the surface, driven by the enormous pressure and high temperature to which it is subjected. Are the quantities of water in the crystallized zone of anamorphism, combined with the pressures and temperatures there, sufficient to give to the water an equally strong tendency to move downward? Whether water makes its way into the zone of anamorphism from the centrosphere below, or moves in the reverse direction, would depend upon the relative force of these two tendencies. Since we know nothing of the quantity of water in the centrosphere, but little as to the condition of the material of that zone, little of the temperatures there prevailing, and absolutely nothing as to a change in the condition of the material in passing from the lithosphere to the centrosphere, I do not venture to express an opinion as to whether or not water travels upward from the centrosphere into the zone of anamorphism. So far as the analogy between the zone of anamorphism and the belt of cementation has any weight, it indicates an upward rather than a downward movement. The permanence of the ocean might be adduced as evidence of the gradual although slow movement of water from the centrosphere to the zone of anamorphism, and from the zone of anamorphism to the belt of cementation, and thence to the surface, rather than a reverse movement. But this movement may be accomplished mainly by volcanism rather than by circulation through the solid rocks.

VARIABLE MATERIALS AND CONDITIONS.

The rocks of the zone of anamorphism include various classes: (1) All kinds of plutonic igneous rocks may be found in the zone of anamorphism. Indeed, the lower zone is especially the zone of the plutonic igneous rocks. It is in this zone that the great batholiths form. Chemically they vary from the most basic to the most acid, and mineralogically they are correspondingly variable. (2) All kinds of sedimentary and all kinds of volcanic rocks may pass into the zone of anamorphism by deep burying.

As sediments are buried under later sediments, the earlier sediments join the lower zone. Volcanic rocks may join the lower zone either by burying beneath later volcanic rocks or by burying below sediments, or both combined. During their downward movement to the zone of anamorphism they undergo the alterations of the belt of cementation. (3) Any of the products of the belt of weathering may be included within the zone of anamorphism. This may follow as a consequence of the transgression of the sea upon a weathered area and subsequent deep burial under sediments. To illustrate, the rocks of the Piedmont Plateau of the United States and of Brazil are disintegrated to a depth varying from a meter to 90 meters. If the sea transgresses over these regions in the future, as it has in the past, without very active erosion, the weathered zone may be buried beneath later sediments, or volcanics may be poured over the weathered rocks and thus protect them. By deep burying, as a result of volcanism or sedimentation, or the two combined, the entire weathered zone may thus join the lower zone. Finally, it is to be remembered that the weathered rocks which join the lower zone by burying necessarily pass through the belt of cementation, or have undergone the modifications of that belt at least to some extent, before joining the zone of anamorphism.

From what has gone before it is clear that there are considerable variations in the conditions of the zone of anamorphism. The pressure and the temperature vary greatly, depending upon depth, deformation, and igneous intrusions; the quantity of injection varies greatly, the igneous material being here very abundant or preponderant and there altogether absent; the quantity of water, while absolutely small, has a wide ratio of range, being many times more abundant under some conditions than under others. Since this agent, although present in small quantity, is a chief agent of transformation, this variation in the quantity of water is very important.

Therefore the conditions are exceedingly varied in the zone of anamorphism. Excluding the effects of intrusives, the changes of conditions generally take place rather gradually, and changing from one set of conditions to another a considerable vertical depth or a greater lateral distance is commonly required. In this respect the conditions contrast with those of the zone of katamorphism. The contrast is especially marked with the belt of weathering, where the variations in conditions are great and

sudden, but less marked with the belt of cementation, where the variations in conditions are somewhat gradual, and therefore approximate in this respect those of the zone of anamorphism.

WORK IN ZONE OF ANAMORPHISM.

As in the zone of katamorphism, the work from a physical-chemical point of view may be divided into mechanical work, chemical work, and igneous work.

MECHANICAL WORK.

Mechanical work comprises welding, strain within the elastic limit, and strain beyond the elastic limit.

WELDING.

Welding is the cohering of the rock particles in consequence of pressure which brings them so close together that they are within the limit of molecular attraction of one another. It has been explained that within the zone of anamorphism the pressures in all directions are greater than the crushing strength of the rocks, and that if openings could be supposed to be produced they would necessarily be closed because of the incapacity of the rocks to support themselves. This pressure is so great that the particles are brought within the limits of molecular attraction, and therefore are welded for the same reason that metals weld under proper conditions. That this conclusion, based upon physical reasoning, is certainly true, is shown by the invariably strong cohesion between the mineral particles of rocks which have been in the zone of anamorphism; and recently this conclusion, founded upon physical reasoning and observation, has been confirmed by the experiments of Adams and Nicolson.[a] They have ascertained that when dry marble is deformed under pressure in all directions greater than its crushing strength, no supercapillary openings form, and the deformed rock has strength only a little short of that of the original marble. Since the deformation was carried on while the rock was dry, the coherence of the rock particles can not be attributed to the action of water, but must be due to true molecular attraction or welding. The rock was therefore deformed under conditions similar to those which often obtain in the zone of anamorphism.

---

[a] Adams, F. D., and Nicolson, J. T., An experimental investigation into the flow of marble: Philos. Trans. Royal Soc. London, ser. A, vol. 195, 1901, pp. 363–401.

In the zone of anamorphism, in consequence of pressure in all directions greater than the crushing strength of the rocks, and the resulting invariably close contact of the mineral particles, the process of welding is of far greater consequence than in the belt of cementation, although it has been shown that in the latter belt welding does take place under favorable conditions. (See pp. 595–597.) In short, while welding is an exceptional process in the zone of katamorphism, it is a universal process for the zone of anamorphism.

The depth at which welding occurs is different for different substances. Such plastic substances as coal and clay may be welded at very moderate depth, while the strong and refractory rocks, such as quartzites, require a very considerable depth.

STRAIN WITHIN ELASTIC LIMIT.

Within the zone of anamorphism all the mineral particles of all rocks are in a high state of strain at all times. Where the conditions have been quiescent for a long time and the mineral particles have readjusted themselves to the conditions, it may be supposed that the stresses are approximately equal in all directions, and therefore that the conditions approach those of hydrostatics. Under such circumstances the pressure would be the same in all directions within a mineral particle, and the only tendency would be to elastically condense it. The strain would be one of simple compression; or putting it in physical terms, negative homogeneous dilatation.[a] The molecules of a given mineral particle, as, for instance, one of quartz, are pressed together by virtue of the elasticity of the mineral, and a given particle occupies less space than under surface conditions, where the pressure is slight. Where the hydrostatic pressure is very great, recrystallization may follow, by means of which the minerals pass into more condensed molecules, as is fully explained under "Metasomatism," and especially in connection with the development of porphyritic crystals. (See pp. 699–705.)

Strain within the elastic limit in which the pressure is equal in all directions is very exceptional, if it ever exists. Almost invariably the pressure is unequal in different directions. The difference in the amount

[a] Hoskins, L. M., Flow and fracture of rocks as related to structure, appendix to Van Hise, C. R., Principles of North American pre-Cambrian geology: Sixteenth Ann. Rept. U. S. Geol. Survey, pt. 1, 1896, p. 860.

of the pressure in the different directions varies from zero to the elastic limit of a mineral particle under the conditions in which it exists. The difference between the stresses in the different directions where they are great in all directions has been called by Darwin the "stress-difference."[a] It has been assumed by Darwin that if a mineral particle or a rock be subjected to stress in all directions, when the stress-difference between the maximum and minimum pressure is as great as the strength of the particle or rock at the surface, deformation by rupture will take place. But this by no means necessarily follows. It is highly probable that a greater stress-difference is required for deformation when the rocks are under pressure in all directions than when the pressure in one direction is zero, as at the surface. Hallock found[b] that when a solid of a certain composition, readily plastic under ordinary conditions, was subjected to a pressure of 6,000 atmospheres in cylinders on one side of which were placed coins and tacks, the plastic substance, instead of flowing around the coins, pressed them against the surface of the cylinder so as to fit it perfectly. Moreover, the coins and the steel tacks were forced against the cylinder so strongly that their impressions were left on the steel holder so as to be seen and felt. From this experiment Hallock concludes that "in general for one and the same substance, over considerable ranges of condition, the rigidity diminishes as the intermolecular distances increase."[c] Or, reversing this generalization to accord with his experiment, the rigidity increases as the intermolecular distance decreases. Now in the zone of anamorphism, where great pressure obtains in all directions, the molecules are brought closer together than at the surface, and probably therefore a much greater stress-difference is required to reach the elastic limit of mineral particles in rocks in the zone of anamorphism than at the surface. How much greater the stress-difference must be it is impossible to conjecture.

This statement applies only to mechanical deformation. In so far as change in form takes place through solution and deposition, or by recrystallization, the above rule does not apply; and this is probably a fact of

[a] Thomson, W., and Tait, P. G., Treatise on natural philosophy, Cambridge Univ. Press, London, edition of 1890, pt. 2, p. 423.

[b] Hallock, William, The flow of solids; or, liquefaction by pressure: Am. Jour. Sci., 3d ser., vol. 34, 1887, pp. 277–281.

[c] Hallock, cit., p. 278.

most profound significance in the metamorphism of rocks, for it will be fully explained under "Metasomatism" that in so far as mineral particles are strained, and especially as they are under unequal strains, in different directions, solution and redeposition is likely to accomplish deformation. (See pp. 690–692.) The materials are dissolved and mineral particles of different shapes are deposited in an unstrained condition. To accomplish this it is not necessary that the stress difference shall equal or even approach that of the elastic limit of the minerals and rocks.

We conclude that strain within the elastic limit, either with or without a stress difference, but almost universally with a stress difference which for much of the zone of anamorphism often exceeds the crushing strength of the rocks at the surface, prevails throughout the zone, affecting every mineral particle, small and great.

Where the stress difference surpasses the elastic limit of the rocks under the conditions in which they exist, rupture may take place, and this leads us to the next section.

STRAIN BEYOND ELASTIC LIMIT.

Strain beyond the elastic limit in the zone of anamorphism results in disruptive deformation, as in the belt of cementation. But the ruptures are very different in the two. During deformation in the zone of anamorphism every particle, small or great, takes part in deformation, and it is this fact which gives a fundamental difference between fracturing in the zone of anamorphism and in the belt of cementation, since in the latter belt between the fractures are blocks, small or great, which do not take part in the movements. In this belt but a small number—in many cases an almost infinitesimal fraction—of the mineral particles are actually ruptured, whereas in the zone of anamorphism strain beyond the elastic limit breaks all particles. If a slide be made from rocks deformed in the zone of anamorphism not one square centimeter can be found in which movement has not taken place. Not only so, but no mineral particle has escaped the effect of the deformation. Where strain has extended beyond the elastic limit, under the microscope the deformed mineral particles are seen to give evidence of the above facts by their undulatory extinction and their granulation. (See fig. 17.)

This contrast in the nature of mechanical deformation between the zone of anamorphism and the belt of cementation is of great significance,

and yet it has almost altogether escaped notice. What stronger mechanical contrast can there be than escape from rupture of all but a very small number of the minerals of a rock and the participation in fracturing of all the mineral particles of a rock? But we shall see that in the zone of anamorphism deformation is largely accomplished by chemical processes, whereas in the belt of cementation deformation is mainly accompanied by mechanical processes, thus presenting an even stronger contrast between the two. (See pp.766–768.)

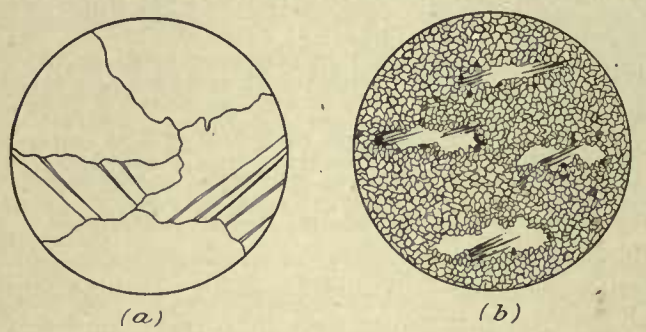


FIG. 17.—Granulation of feldspar, and gradation between undulatory extinction and granulation. (a) normal anorthosite; (b) granulated anorthosite. After Adams.

The amount of granulation varies greatly, depending upon the minerals, the size of the particles, and the amount, rate, and other conditions of deformation. Some minerals are much more readily granulated than others. For instance, in many rocks containing quartz and feldspar the former mineral may be granulated while the latter mineral is but little affected. (See fig. 18.) The granulation of a particle may be peripheral or extend throughout the particle. At a stage of deformation, when the smaller particles are granulated throughout, the larger particles may suffer only peripheral granulation; in a more advanced stage the larger particles may be granulated throughout; and in some cases of extreme deformation the largest bowlders of conglomerates are mashed into thin layers not recognizable as clastic fragments, each being composed of a multitude of particles. The degree of subdivision by granulation in cases of extreme deformation is not usually realized. It should be recalled in this connection that the volumes of particles are as the cubes of their diameters. Very often the diameters of the granulated particles are not more than .1 the diameters of the original fragments; rather frequently they are not more than .01, and in some cases they may not be more than .001 of the originals. This means a subdivision of the original particles into 1,000, 1,000,000,

FIG. 18.—Granulation of quartz in a rock in which the feldspar is but little affected. (a–a) granulated quartz; (b) feldspar. After Adams.

and 1,000,000,000 particles, respectively. One of the best illustrations of mechanical granulation is that of the anorthosite described by Adams.[a] Mr. S. H. Ball has compared the size of the grains of the original anorthosite and the granulated anorthosite in two specimens furnished by Dr. Adams, and found that, on the average, one feldspar grain of the original rock is broken into 70,000 grains.

By granulation the volume is sure to be somewhat increased, for it is not possible that the broken particles of a grain shall fit so closely as they did when all were parts of one crystallographic unit. The subcapillary openings between the particles may be very small, but they are not so minute as to be ignored. Also, not infrequently small capillary openings form between the granules, and these considerably increase the volume.

Mügge[b] has shown that ice crystals may be mechanically deformed by differential movement along gliding planes without the destruction of the crystals. Adams and Nicolson[c] have shown by experiment that the same process may occur in calcite crystals; and they thus largely explain the deformation of many of the marbles. This process is essentially mechanical strain beyond the elastic limit. In so far as gliding takes place, deformation may occur without diminution in size of the mineral particles, and hence it contrasts very strongly with granulation. It is notable that in the experimental deformation of marble by gliding, the mineral composing the rock is one in which there are numerous gliding planes, and how important this process may be in reference to other minerals is more or less conjectural. Doubtless it is of some consequence in such minerals as have good gliding planes—for instance, the micas; but probably it is of little consequence with the greater number of the rock-making minerals, such as quartz, feldspar, the pyroxenes, and amphiboles.

CHEMICAL WORK.

The chemical work of the zone of anamorphism, like that of the belt of cementation, must be considered from two points of view—the chemical changes and the resultant processes.

---

[a] Adams, F. D., Report on the geology of a portion of the Laurentian area lying to the north of the Island of Montreal: Ann. Rept. Geol. Surv. Canada, new ser., vol. 8, 1896, pt. J, pp. 31–85.

[b] Mügge, O., Ueber die Plasticität der Eiskrystalle: Neues Jahrbuch für Mineralogie, etc., Jahrgang, 1895, vol. 2, pp. 211–228.

[c] Adams, F. D., and Nicolson, J. T., An experimental investigation into the flow of marble: Philos. Trans. Royal Soc. London, series A., vol. 195, 1901, pp. 363–401.

CHEMICAL CHANGES.

The chief chemical changes in the zone of anamorphism comprise deoxidation, silication, dehydration, and solution and deposition.

It is commonly true that the reactions of deoxidation, silication, dehydration, and solution and deposition do not occur separately, but two or more together; yet, in order to clearly understand their effect, each is considered separately.

DEOXIDATION.

Many of the sedimentary rocks contain organic material. In some cases, at least, the deep-seated igneous rocks contain metallic iron, and often they contain sulphides, among which bisulphide of iron is the most important. The zone of anamorphism is deep below the surface, so that oxygen can not get into it from the surface of the earth. Indeed, it has been shown that the oxygen which passes downward with the surface waters is usually exhausted before it has gone far into the belt of cementation. It follows that the solutions of the zone of anamorphism are reducing, and the conditions those of deoxidation. Therefore highly oxidized compounds are likely to be partly reduced. Ferric oxide is the most important of such compounds. This compound may be reduced to the ferrosoferric state, forming magnetite, or to the ferrous state, in which form it is in a favorable condition for silication. The amount of reducing agents which are present in the zone of anamorphism is very variable. For instance, the sediments may have almost no organic matter or they may have a great, even a predominant, quantity. Where reducing agents are abundant little or none of the iron is likely to remain as ferric oxide. Where, on the other hand, organic material is sparse and there are large quantities of ferric oxide this may permanently remain in this state. Where deoxidation occurs there is a decrease in volume, but in most cases the amount is small.

In the above paragraph it is supposed that deoxidation takes place only if a reducing agent be present. There is no evidence that the pressure may be so great that oxygen is squeezed out because of the demand for decreased volume, although such a reaction is theoretically possible if the pressure were high enough.

SILICATION.

In Chapter IV (p. 168) silication has been defined as the union of silica with bases so as to produce silicates. In that chapter the close analogy between the silicates and the carbonates has been pointed out, as well as one of the most fundamental facts of metamorphism, their mutual interchange. (See pp. 173–177). In the chapters on the zone of katamorphism it has been seen that the carbonation of the silicates is one of the processes of fundamental importance, and in the belt of weathering the one which has the most far-reaching effects. It has further been explained that in the zone of anamorphism this process is reversed, silica replacing carbon dioxide of the carbonates and producing silicates. While silica in the zone of anamorphism unites with bases not previously combined with carbon dioxide, it is probable that silication of this kind is unimportant. It is certain that much of the free silica which unites with bases in the zone of anamorphism simultaneously drives off carbon dioxide. There are a number of silicates which are formed by the direct silication of a single mineral. To illustrate: silication of calcite forms wollastonite; silication of dolomite forms tremolite and wollastonite; silication of ankerite forms sahlite and actinolite; silication of siderite forms grünerite. Frequently silication requires two or more minerals to produce the new silicate. As instances, we have the silication of rutile and calcite together, producing titanite; of hypersthene and calcite, producing actinolite and anthophyllite; of olivine and calcite, producing actinolite; and of dolomite and siderite, or ferrous dolomite, producing anthophyllite. Silication usually does not occur alone, but takes place in connection with deoxidation or dehydration, or both. As a case where we have silication with dehydration may be mentioned the silication of gibbsite, producing sillimanite and cyanite. A case of silication with deoxidation and dehydration is the formation of grünerite from limonite. But usually the instances of silication combined with deoxidation or dehydration, or both, are so complex that it is impossible to state what particular combinations of minerals are deoxidized, dehydrated, or both, and silicated in order to produce a definite silicate.

It will be seen in Chapter IX, when rocks are considered, that this process of silication takes place on a vast scale. Indeed, no sooner does a carbonate pass from the zone of katamorphism to the zone of anamorphism

than silication of the carbonates, with decarbonation, takes place. In many of the ancient formations the process of transformation has been complete; in others it is far advanced, and it is uncommon to find any carbonate formation that is buried in the zone of anamorphism in which the process has not taken place to an important extent.

It has been explained (pp. 665–667) that a portion of the carbon dioxide and water freed by silication probably escapes to the belt of cementation and thence to the surface. It will be seen on pages 970–971 that one of the important sources of carbon dioxide for the process of carbonation is the vast quantity which comes to the surface through ground waters. Illustrating this is the startling case furnished by Lecoq, who says that the mineral springs in Auvergne district annually give off 7,000,000,000 cubic meters of carbon dioxide;[a] and the immeasureably greater amount which reaches the surface for the world as a whole is mainly carbon dioxide freed by the process of silication in the zone of anamorphism. This idea, that the carbon dioxide which reaches the surface from subterranean sources is that derived from the carbonates produced in previous geological ages, was first suggested by Bischof.[b]

However, a part of the carbon dioxide and accompanying water does not escape, and this is believed to largely explain the innumerable cavities partly filled with water and carbon dioxide which are so generally found in the sedimentary rocks metamorphosed in the zone of anamorphism. Such inclusions are comparatively rare, although not unimportant, in the original igneous rocks. (See p. 969.) Silication is thus offered as a cause which explains a large proportion of the liquid carbon dioxide inclusions in the rocks.

Commonly when the silicated rocks have reached the surface, so that thin sections may be cut, liquid carbon dioxide and water do not entirely fill the cavities, a part being occupied by the gases of these compounds. Doubtless in the deep-seated zone where the rocks were altered the carbon dioxide and often the water were above their critical temperature, and were altogether in the form of gas. Possibly if accurate measurements were made of the volumes of water, liquid carbon dioxide, and water and carbon-dioxide gas, and the total volume of many of the openings in a rock, so as

[a] Blake, R. F., and Letts, E. A. The carbonic anhydride of the atmosphere: Sci. Proc. Royal Dublin Soc., new series, vol. 9, pt. 2, 1900, p. 159.

[b] Bischof, Gustav, Elements of chemical and physical geology, translated by Paul and Drummond, Harrison & Sons, London, vol. 1, 1854, pp. 237–241.

to get average determinations, this might enable one to arrive at alternative conclusions as to the pressures and temperatures under which the alterations took place. If a given temperature were assumed, the pressure, and therefore the depth, could be calculated. If, on the other hand, pressure were assumed, the temperature could be calculated.

Silication involves decrease in volume, varying from a very small amount to 40 per cent or more. In the silication of the carbonates, if the freed carbon dioxide be supposed to escape, the decrease in volume is usually between 20 and 40 per cent, and averages fully 30 per cent. In so far as there are cavities that are filled with the water and carbon dioxide which have been liberated by the processes of silication and dehydration but have not escaped, the above determinations as to diminution of volume are too great. No estimates of the volumes of these inclusions in the metamorphic sedimentary rocks have been made, but the average amount would probably be comparatively small, possibly less than 1 per cent, although in certain of the schists and gneisses the amount would be much greater than this.

DEHYDRATION.

It has been seen in the previous chapters (Chapters IV to VII) that hydration is one of the most important and characteristic of the reactions which occur in the zone of katamorphism. By that process alone or combined with others a large number of hydrated minerals are formed. The most important of these comprise the hydrous silicates and the hydrous oxides. The hydrous silicates include the kaolin group, the serpentine-talc group, the chlorite group, the hydromica group, the zeolite group, and the epidote group. The oxides include the aluminum-oxide group, of which gibbsite is the most important, and the iron-oxide group, of which limonite is the most important. In the zone of anamorphism all these minerals are dehydrated; but in general one can not assert that from a definite one of them some other definite mineral is produced, for commonly during the time of dehydration other alterations also take place, and commonly the materials of two or more minerals unite to produce a new mineral. However, in some cases the alteration is that of simple dehydration; as, for instance, hematite is formed from limonite, anhydrite is produced from gypsum, quartz is formed from opal, corundum develops from gibbsite. By the process of simple dehydration there is usually a very considerable decrease in volume, running from 20 to 40 per cent.

It is believed that the process of dehydration is largely caused by pressure. In other words, water is actually separated from its combination and made free water by the pressure, and the freed water is squeezed out of the rocks as water from a sponge. Undoubtedly, also, the increase of temperature with depth promotes dehydration. Without exhaustive experimental work it is impossible to give any quantitative estimate of the relative importance of pressure and temperature in producing dehydration. While it is certainly true that moderate pressures and temperatures together rapidly produce dehydration of the more hydrous minerals, ordinarily pressure and temperature are not sufficiently great to drive off all water. Apparently liberation becomes more and more difficult as the water increases in amount. Dehydration is always incomplete, and commonly does not reduce the combined water below 1.5 per cent. (See pp. 742–744.)

It is probable, as explained on pages 665–667, that the larger part of the freed water escapes upward to the belt of cementation, but some part of it is confined in the altered rocks. Thus dehydration explains a large portion of the water inclusions in the metamorphosed rocks. Of course the water inclusions of original igneous rocks are explained differently, although in an analogous manner. The water, or a part of it, occluded in the magmas, separates at the moment of crystallization, and such part as can not escape is included by the crystallizing minerals.

SOLUTION AND DEPOSITION.

Solution and deposition are essential concomitants of the chemical reactions of deoxidation, silication, and dehydration, as well as of all other important chemical changes. Cementation, next considered, involves deposition. In metasomatism, subsequently treated, recrystallization is the change of greatest consequence, and this is accomplished almost wholly by solution and deposition.

Whether solution is preponderant in the zone of anamorphism, or the reverse process, deposition, it is difficult to say with certainty. But if intrusives be ignored, probably solution is slightly preponderant. Elsewhere it is shown that there is no evidence of transfers of material into the zone of anamorphism by the water solutions. (See pp. 665–668, 764–766.) By deoxidation, silication, and consequent decarbonation, and by dehydration, the solids constantly lose material. The water as a whole moves from the

zone of anamorphism to the belt of cementation (see pp. 665–667), and takes with it the freed materials and all the other compounds it can hold. Hence, under normal conditions, solution probably somewhat overbalances deposition; but where igneous instrusions occur the above reasoning is inapplicable.

RESULTANT PROCESSES.

The processes resulting from the chemical changes comprise cementation and metasomatism.

CEMENTATION.

Cementation in the zone of anamorphism is of far less importance quantitatively than in the belt of cementation. The openings are mainly confined to those of microscopic size—i. e., to the capillary openings between the mineral particles and to the innumerable subcapillary openings. There are in this zone no large openings. The laws of deposition within the minute openings are the same as in the belt of cementation, and will therefore not be repeated. However, the minerals produced are those characteristic of the zone of anamorphism rather than those of katamorphism.

The list of these minerals is deferred to the next section on metasomatism, since that process is far more important than cementation. While the quantity of cementing material in the zone of anamorphism is small, it is not unimportant, at least so far as the strength of the rocks is concerned. If after deformation the new openings between the particles were not occupied by mineral material, the rocks would be rather weak. When, however, these particles are cemented by deposition, they may become as strong as or stronger than they were before deformation.

That cementation actually does take place in the minute openings between the grains is shown by the experimental work of Adams. When marble was deformed without water the modified rock was weaker than the original marble, but where water was present, under great pressures and at high temperatures, in one case the deformed rock was actually stronger than the original marble, thus showing that cementation caused the grains to cohere more strongly than when simple welding was the cause of cohesion, as in the case of deformation where water was absent.[a]

---

[a] Adams, F. D., and Nicolson, J. T., An experimental investigation into the flow of marble: Philos. Trans. Royal Soc. London, ser. A, vol. 195, 1901, pp. 370–385.

It has been seen (pp. 663–664) that the migration of water through the discontinuous minute openings is exceedingly slow. Therefore the transfer of material in any considerable amount and for great distances is very slow. It follows that the process of cementation is confined to the deposition of material in the minute microscopic spaces, and, ignoring injections, that this material is mainly if not wholly derived from the body of the adjacent rock. In this respect there is a marked contrast between the zone of anamorphism and the belt of cementation. It has been pointed out on pages 617–619, 656, that in the latter belt the material deposited may be great in quantity and derived from points remote from deposition. It follows that, so far as the process of cementation is concerned, the chemical composition of the rocks is little changed in the zone of anamorphism; whereas, as has been shown on pages 655–656, in the belt of cementation the chemical composition may be greatly changed by this process.

METASOMATISM.

Metasomatism in the zone of anamorphism may take place in various ways, the same as in the belt of cementation. A mineral may recrystallize without change in chemical composition, as, for instance, the alteration of tridymite to quartz. Two or more minerals may unite to form a single mineral, as, for instance, the union of calcite and quartz, producing wollastonite. A mineral may change into two or more minerals, as, for instance, kaolinite into andalusite and quartz, but this class of reactions is much more common in the belt of cementation. One mineral may be replaced by another, as, for instance, the substitution of magnetite for quartz. Two adjacent minerals may react upon each other, producing a third mineral, as, for instance, bytownite and olivine, producing amphibole.[a] But more frequent than any of these simple reactions are complex changes by which the materials from a number of minerals rearrange themselves to produce more than one new mineral. These various reactions between the minerals are mainly accomplished, as usual, through the medium of the water solutions.

There are important differences between metasomatism in the zone of anamorphism and metasomatism in the belt of cementation. In this zone

[a] Williams, Geo. H., The gabbros and associated hornblende rocks occurring in the neighborhood of Baltimore, Md.: Bull. U. S. Geol. Survey No. 28, 1886, p. 52.

the water solutions are in minute openings, in small quantity, and circulate slowly; therefore, it can not be supposed that any considerable amount of material is contributed from an outside source except by injection. This subject is more fully discussed later. (See pp. 764–766.) The reactions which occur are in the direction of deoxidation, silication, and dehydration, instead of in the direction of oxidation, carbonation, and hydration. The minerals formed comprise practically all of the important heavy anhydrous minerals.

MINERALS FORMED.

Among the minerals formed in the zone of anamorphism are the following:

The carbon minerals are anthracite, graphite, or diamond.

The abundant sulphides are pyrite and pyrrhotite. Marcasite, having lower symmetry and lower specific gravity than pyrite, is rare or altogether absent, although abundant in the belt of cementation.

The important oxides are those of silicon, iron, aluminum, and titanium. Silica is found in the form of chert, chalcedony, or quartz. Tridymite is not known. Tridymite alters to quartz because of the higher specific gravity of the latter mineral. Iron oxide occurs in hematite, magnetite, and ilmenite. Aluminum oxide occurs as corundum. Titanium oxide is found as rutile, octahedrite, and brookite. The two latter are rare as compared with rutile. This is probably explained by the fact that the latter mineral occupies less volume. The absence of the hydrous oxides, such as limonite, gibbsite, brucite, etc., is explained by the general fact of dehydration characteristic of the zone of anamorphism.

The carbonates, aragonite, magnesite, dolomite, siderite, ankerite, and parankerite are extensively recrystallized; but the processes as a whole tend to destroy them, forming silicates. Ordinarily, where the carbonates were in large volumes, the process of silication and decarbonation is incomplete.

The most important sulphate is anhydrite. Gypsum does not occur, because the process of dehydration destroys it. Titanate as titanite, and phosphate as apatite, occur.

Practically all the important anhydrous silicates are abundant. These comprise the feldspars, the pyroxenes, the amphiboles, the nephelite-sodalite-leucite group, the garnets, the olivines, the scapolites, the epidotes,

allanite, chondrodite, andalusite, sillimanite, cyanite, staurolite, tourmaline, the micas, chloritoid, and ottrelite; and of course various subordinate silicates, such as axinite, melilite, gehlinite, vesuvianite, zircon, piedmontite, topaz, etc. The only silicates which bear appreciable amounts of water are the epidotes, staurolite, and the micas. The ordinary compression conditions of the zone are not strong enough to completely dehydrate these minerals. It therefore appears that the most profound conditions of metamorphism with which we are familiar are not sufficient to drive off all of the water from all the minerals.

It has been explained that the hydrated, carbonated, and highly oxidized minerals produced in the zone of katamorphism may, when buried, pass into the zone of anamorphism. It has also been explained on pages 366–369 that in these two zones the reactions are reversed. However, it by no means follows that when a rock altered in the belt of weathering or the belt of cementation has passed into the zone of anamorphism the minerals originally present in the rock will be reproduced in their original proportions. Indeed, it is certain that this will rarely, if ever, occur. The reason for this is that in the zone of katamorphism, and especially in the belt of weathering, there may have been great changes in the chemical composition of the rocks. For instance, it has been pointed out that the rocks are very much depleted in alkalies and alkaline earths in the belt of weathering, and that in the belt of cementation the addition of silica is very common. It is therefore clear that when rocks of changed chemical composition pass into the lower zone the minerals which were originally present before the rocks were altered in the zone of katamorphism may not all be reproduced, nor will those there formed develop in the same proportion as originally. Furthermore, the sediments are likely to be deficient in certain elements as compared with original igneous rocks. One element which is especially deficient in these is sodium. It naturally follows that when a sedimentary rock is transferred to the zone of anamorphism by burying, such soda minerals as leucite, nephelite, and sodalite are rarely, if ever, produced, simply because of a deficiency of one of the elements out of which they may be made. But even where unchanged igneous rocks are recrystallized in the zone of anamorphism the minerals are not preserved in the same proportion, for it has been explained that pressure tends to produce molecules which are heavy, and consequently

such minerals as garnet, staurolite, and other heavy minerals form by the metamorphosis of many of the igneous rocks without any necessary change in average chemical composition.

Not only may such changes as those given occur, but there may be repeated changes. These are especially likely to occur with changes in the pressure conditions. Under the law that the greater the pressure the heavier the minerals formed, there may be repeated recrystallizations of the rocks. Minerals produced at an early stage under conditions of moderate temperature and pressure are destroyed and minerals of higher specific gravity are produced. Thus a mud may change to shale, thence to slate, thence to mica-slate, thence to andalusitic micaceous schist, thence to garnetiferous, staurolitic, and cyanitic micaceous schist or gneiss. In proportion as the pressure is great and the temperature high, the tendency is to produce heavier and heavier minerals. Thus a rock which had become more and more deeply buried may be recrystallized, or partly so, a number of times, minerals of higher and higher specific gravity successively appearing. It is entirely possible that in the deeper part of the lithosphere and within the centrosphere unknown minerals are produced which are heavier than any formed in the part of the lithosphere which has reached the surface as the result of denudation. In this connection it is noteworthy that the majority of the heavy silicate minerals developed in the zone of anamorphism are those which, so far as they have been artificially produced, have been formed either under igneous conditions or, if water were present, under conditions of very high pressure and temperature. The latter is notably the case for amphibole, pyroxene, quartz, and adularia, which were obtained by Chrustschoff from aqueous solutions heated to a temperature of 550° C.[a]

Metasomatism in the zone of anamorphism may take place under mass-mechanical or mass-static conditions. The modifications under these two sets of conditions are so different that it will be necessary to consider them separately.

ALTERATIONS IN CONNECTION WITH MASS-MECHANICAL ACTION.

It has been seen that where deformation in the zone of anamorphism is accomplished by rupture alone the result is ever to subdivide the rock particles. (See pp. 673–675.) It was there indicated that under other

[a] Chrustschoff, K. von, Ueber künstliche Hornblende: Neues Jahrbuch, vol. 2, 1891, pp. 86–90.

circumstances deformation is mainly accomplished, not by mechanical subdivision, but by the chemical action of recrystallization. The fundamental idea of this process is that as the rock is deformed it takes the new form necessary by means of solution and redeposition of the rock material. But this process is accompanied by strain within and beyond the elastic limit of the minerals. In considering recrystallization these facts also are necessarily taken into account. In order to make this clear the facts of recrystallization will first be considered, and then the theory.

RECRYSTALLIZATION.

Facts of recrystallization.—One would expect, from the section on strain beyond the elastic limit, that the more profound the kneading the finer would be the granulation of the altered rock, but this is not the case. Many of the most profoundly deformed rocks, instead of being extremely fine-grained, are somewhat coarsely crystalline.

This anomaly was long a puzzle to me. In examining the deformed rocks, I found that under certain conditions the more profound the deformation the finer the granulation; but in tracing the process to the extreme, I found that there was always a limit beyond which the particles did not become more finely granulated. On the contrary, at a certain stage a reverse tendency appeared, and the particles, instead of becoming smaller, gradually became larger. This increase in coarseness of the mineral particles may be followed through all stages to the coarse schists and gneisses.

In the granulated rocks the mineral particles everywhere show strongly the strains of undulatory extinction, but the mineral particles of many of the coarse schists and gneisses show no more than slight strain shadows. The coarse, perfect schists and gneisses, nearly free from strain shadows, are always found to be those which have been deeply buried and profoundly deformed or which are adjacent to great intrusive masses, or both. It is therefore clear that those rocks represent the most advanced stages of metamorphism.

It is generally agreed that the schists and gneisses of this character have been recrystallized throughout, and therefore strongly contrast with those rocks which have been granulated. However, the granulated and recrystallized rocks are not separated sharply from each other (see pp.

766–768); on the contrary, there is every gradation between the two. The original rock may have varied greatly in the coarseness of its constituent particles. If one passes from a place of granulation to a place of recrystallization, one may find that recrystallization of the matrix begins while granulation of the larger particles is still going on. In an intermediate stage the matrix may have completely recrystallized and the granulation of the coarser particles be still incomplete. As a consequence, the mineral particles of the matrix are increasing in size at the same time the larger particles are decreasing in size.

At a certain stage the larger grains are granulated into particles which average about the same magnitude as those which have crystallized out of a fine-grained and perhaps irresolvable matrix, and, moreover, the grains which have formed from the matrix approximate uniformity of size. Thus there is a marked tendency toward uniformity in the size of the grains of the metamorphosed rocks, and this tendency is ordinarily dominant in the schists and gneisses so long as mass deformation continues. (Pl. XI, *C*.) This statement is more nearly accurate in reference to the particles of each mineral than to particles of different minerals. This tendency toward uniformity controls notwithstanding the principle that under ordinary conditions large minerals grow at the expense of smaller ones (see Chapter III, pp. 74–76); for under mass-mechanical conditions a large grain, whether original or produced by uneven growth, is especially exposed to the mechanical stresses, and therefore is granulated in part or put into a state of strain, and thus is more readily attacked by the solutions. Some of the properly oriented smaller particles may themselves grow at the expense of the larger ones or of the small ones not properly oriented or happily placed. Thus is explained the characteristic uniformity in the size of the particles of the schists and gneisses which have not been modified since mass-mechanical action ceased. However, in some cases, where the mineral particles are properly oriented, the tendency for large individuals to grow at the expense of smaller ones may control, and porphyritic textured schists and gneisses be produced. (Pl. III, *C*, *D*.)

Such an occurrence is beautifully illustrated by the albite-schist of Hoosac Mountain, Massachusetts, described by Wolff.[a] Here there are

[a] Pumpelly, Raphael, Wolff, J. E., and Dale, T. Nelson, Geology of the Green Mountains in Massachusetts: Mon. U. S. Geol. Survey, vol. 23, 1894, pp. 59–63.

numerous porphyritic, simple twinned albites, with a close approximation to definite orientation, the two greater dimensions of the crystals lying in the planes of schistosity. Similar phenomena in reference to feldspar are shown by some of the augen-gneisses. Not infrequently porphyritic mica and chloritoid show approximately similar orientations. In some cases porphyritic staurolites have their greater dimensions arranged approximately in the schistose planes. In such cases as these the fortunate positions of the porphyritic crystals are such that the tendency for large individuals to grow at the expense of small ones is sufficiently strong to prevent the usually dominant tendency to destroy large individuals, and thus to prevent the production of the even-grained texture which is normally characteristic of the schists produced during mass-mechanical movement.

In the case of an isometric mineral, such as garnet, which has no cleavage and an isometric habit, it may be possible for porphyritic crystals to develop during mass-mechanical movement, although it is believed not to be common at least for undistorted crystals, for such growth would imply that minerals of this kind are able to grow as far against the greatest pressure as in the direction of least pressure.

The second characteristic feature of the recrystallized slaty, schistose, and gneissose rocks is that the mineral particles show a marked tendency toward regular orientation. This orientation may consist in the particles having major, mean, and minor diameters in approximately common directions, or in certain species having their crystallographic axes in nearly common directions, as a result of which the like cleavages of all the particles of a given mineral are approximately in the same plane, or in the two combined. (Pl. XI, *C.*) Orientation, where marked, gives the rocks a cleavage.

The most important of the minerals the particles of which show similar crystallographic orientation are the micas, especially biotite and muscovite. With these minerals similarity of orientation is usual. Another set of minerals the particles of each of which frequently show a marked tendency toward similar crystallographic orientation are chlorite, amphibole, and feldspar. Other less important minerals are known to show the same phenomena. Of course, it is understood that the crystallographic orientation is in no case perfect, but with the micas it may approach perfection. From the extreme of regularity of orientation shown by mica in

the typical schists to the random orientation of some of the minerals in the same rocks there are gradations; also there are gradations from the schists recrystallized under mass-mechanical conditions to rocks recrystallized under mass-static conditions where none of the minerals show a marked tendency to similar crystallographic orientation.

In many cases the similar orientation of mineral particles in a typical schist or gneiss may have been greatly disturbed by subsequent deformation near the surface, and therefore in the zone of fracture. Under such conditions shearing fractures may be produced parallel to the slatiness or schistosity, and the shearing motion between the layers may largely destroy the original regularity of the orientated particles.

The particles of some of the mineral constituents of igneous rocks which have not been recrystallized show a tendency toward parallel crystallographic orientation. With this structure are other structures characteristic of rocks crystallized from a magma. I know of but few instances where unaltered igneous rocks so closely resemble the recrystallized schists and gneisses that there is great trouble in distinguishing them.

In the production of the characteristic textures and structures of the slates, schists, and gneisses, the original textures and even the structures may be destroyed, whether they be those of sedimentary or those of igneous rocks. In passing from an area metamorphosed under mass-static conditions to an area altered during mass-mechanical action, often all stages of destruction of the original textures and structures and the development of new textures and structures may be seen. In an intermediate stage the larger particles or more refractory minerals may show the textures of the original rock, the matrix of the same rock, however, having the texture of a slaty or schistose rock. In instances of extreme alteration under mass-mechanical conditions no trace of the original textures remains, even where the rocks were coarse conglomerates or coarse porphyritic, igneous rocks; and the secondary structures may traverse the directions of the original structures and the latter may be wholly obliterated.

Thus metamorphism under mass-mechanical action stands in sharp contrast to metamorphism during mass-static conditions, in so far as textures and structures are concerned. In metamorphism during mass-mechanical action there is a tendency to destroy old textures and to produce a characteristic texture, the more important features of which are mineral particles

of uniform size and parallel orientation, and there is a tendency to destroy old structures and to produce a characteristic slaty or schistose structure. In metamorphism under mass-static conditions original textures and structures are usually preserved, although they may be somewhat modified or emphasized by the unequal size and lack of orientation of the newly-developed mineral particles.

Theory of recrystallization.—Where recrystallization occurs in the deep-seated zone the temperature is considerably higher than at the surface, because of the increase of temperature due to depth, because of heat resulting from mechanical action, and in many districts because of heat derived from intrusive igneous rocks. Water occupies all the openings, including those of subcapillary size. Moreover, this water has about the temperature of the adjacent rocks, and is therefore extremely active. Taking the ordinary gradient, the temperature at a depth of 3,000 meters would be 100° C.; at 6,000 meters, 200° C.; and at 9,000 meters, 300° C. At these temperatures the material would ordinarily be water and not steam, for, ignoring the rock pressure, the pressure of the superincumbent column of water is more than sufficient to prevent it from passing into the condition of a gas. But in consequence of the heat of mechanical action or of igneous intrusion, or both, the temperature at a given depth may be so high that the water may, at least locally and for short times, be in the form of a gas. During the mass movements of rocks water as liquid makes its way between the rock particles much more readily than under conditions of quiescence. (See p. 664.) Therefore the water, on account of high temperature and comparatively free movement, is in a most favorable condition for work.

It has been pointed out (p. 98) that during orogenic movements the rock pressures vary from place to place and from moment to moment. This results in great variation in the pressure upon the contained water. When the pressure increases, solution takes place; when it decreases, deposition occurs. Therefore, in consequence of changing pressure during orogenic movement the conditions are favorable for alternate solution and deposition. Since the pressure continuously varies throughout long periods of orogenic movement, it is probable that this is a factor of very considerable importance in the recrystallization of the rocks.

Another factor which is of great importance in recrystallization is the potentialized energy which exists in mineral particles in consequence of a

state of strain. It has been seen on pages 95–98 that state of strain is very favorable to chemical action. This follows from the principle of the conservation of energy. So far as minerals are in a state of strain, energy is potentialized. This conclusion has been fully verified by Barus,[a] who showed experimentally that when metals are strained a large amount of energy is potentialized; and, finally, Hambuechen[b] has shown experimentally that strained metals are much more easily acted upon chemically than unstrained metals. Therefore the experimental work of Barus and Hambuechen together has completely demonstrated that a state of strain in substances is favorable to chemical action.

It has been shown (pp. 671–673) that all mineral particles in the zone of anamorphism are in a high state of strain. It has been further noted that the stresses may vary from equality in all directions to those so unequal as to approach or surpass the elastic limit of the rock under the conditions in which it exists. Therefore, the mineral particles may be strained within the elastic limit or to the point of granulation; and with the latter the former occurs, for even where the original mineral particles are broken the individual granules ordinarily show strain shadows in polarized light. The condition of unequal stress and strain is especially characteristic of mass-mechanical action. (See pp. 670–672.)

It follows from Barus's and Hambuechen's work that in this interior state of strain of the mineral particles, and especially in unequal strain, we have a cause for recrystallization. The simplest illustration of the effect of a state of strain is perhaps furnished by glass. It is well known that unannealed glass is in a strained condition. This is best illustrated by Prince Rupert's drops. When a point is broken the glass explodes, breaking into powder, showing that a large amount of energy is potentialized. Unannealed glass, even in the laboratory and without the presence of water, slowly releases itself from strain by recrystallization. Corresponding with this fact it is to be expected that ancient natural glasses, because of their unannealed condition, would have released themselves from strain by recrystallization; and such are the facts.

We conclude from the above that the state of strain, and especially unequal strain combined with high temperature in the presence of water, is

[a] Barus, C., The mechanism of solid viscosity: Bull. U. S. Geol. Survey, No. 94, 1892, pp. 107–108.

[b] Hambuechen, C., An experimental study of the corrosion of iron under different conditions: Bull. Univ. of Wisconsin No. 42, 1900, p. 255.

a sufficient cause to produce recrystallization of rocks. As soon as movement begins, equilibrium is disturbed and the processes of solution and deposition or recrystallization set to work rapidly to adjust the minerals.

The amazing power of heated water in solution and deposition, or in recrystallization, has already been pointed out on pages 79–81, and it may be recalled that Barus has shown that above 200° C. glass and water are miscible in all proportions.[a] At temperatures as high as or higher than this, which undoubtedly prevail in the deep-seated zone of deformation, recrystallization can go on with comparative rapidity. At any moment the substances are present almost wholly as minerals. However, superheated water is in the capillary and subcapillary spaces between the particles, and through this as a medium adjustment by solution and deposition goes on continuously during the deformation. At any given moment only an exceedingly small part of the material is in solution; but under the molecular theory of solids all materials in a state of strain, or subject to unequal pressure, or not in a compact state, will be more ready to part with their molecules than the minerals not so conditioned. Thus, from all mineral particles which are under one or all of these conditions, particles are filed off or solution is constantly taking place. Simultaneously with this, from the solutions there is deposition of material in more compact molecules than those dissolved at the places where the pressure on the mineral particles is less than the average.

Two minerals that excellently illustrate the process are quartz and mica. The first recrystallizes somewhat readily and the second develops on an extensive scale in the schists and gneisses. That quartz occurs abundantly in flat individuals in the schists is well known. Moreover, it is known in some cases that the flat individuals are largely the equivalent of individual crystals which have had a nearly spherical form. As illustrations of flat grains of this mineral are the quartzes of the quartz-porphyries described by Futterer[b] (Pl. III, *B*) and of the schists from the Black Hills[c] (Pl. XI, *C*), which I have described. The many flat particles have exactly the appearance they would have had if the material could have been pressed out and

[a] Barus, C., Remarks on colloidal glass: Am. Jour. Sci., 4th ser., vol. 6, 1898, p. 270. See also Am. Jour. Sci., 4th ser., vol. 9, 1900, pp. 167–168.

[b] Futterer, Karl, Die "Ganggranite" von Grosssachsen, und die Quartzporphyre von Thal im Thüringer Wald. Heidelberg, 1890, pp. 27–47.

[c] Van Hise, C. R., The pre-Cambrian rocks of the Black Hills: Bull. Geol. Soc. America, vol. 1, 1890, pp. 222–226, 244.

had recrystallized anew as a single individual and subsequently had been somewhat strained. In some cases the flat individuals have a somewhat curved form. (Pl. III, *B;* also, see p. 753.) The phenomena are believed to be due to solution and deposition, or recrystallization, as already explained. The particles of the quartz not fortunately oriented or at places of great strain are taken into solution and transported to fortunately oriented individuals or those less strained, and redeposited; or, the material dissolved from the more strained part of a grain may be deposited on another part of the same grain where the strain is less. Thus the quartz of a given flat granule may be largely the same quartz as that of the original grain, but it has been dissolved and redeposited in part, perhaps repeatedly.

Were the quartz grains to be granulated the volume of the rock would be increased. (See pp. 674–675.) But by the process of solution and deposition above described the form of the grain is changed and no increase in volume results. Therefore, in the zone of anamorphism, where pressure is the dominant force, recrystallization rather than granulation takes place where it can, for by so doing the volume remains the same even if the grains remain of the same average size, and heavier minerals are not formed; and the volume is decreased where many grains merge, as cited below, and where heavier minerals are produced.

Micas, especially biotite and muscovite, are very abundant in the slates, schists, and gneisses. Moreover, in proportion as the rocks approach typical schists and gneisses the particles of these minerals are large, of approximately uniform size, and oriented crystallographically. (See Pl. XI, *C.*) In the original pelites, from which the micaceous schists most extensively form, the micas are not abundant constituents. Even in the psammites, where allogenic micas occur, the particles are large, more or less irregularly arranged, often somewhat decomposed, and are readily discriminated from the regularly arranged, fresh micas of the schists. These facts are so well known that nearly all petrographers who have studied thin sections of the schists have regarded the micas as authigenic. Chemical analyses show that soils, muds, clays, and shales contain the elements out of which mica may develop.[a] Many of these elements occur in hydrated compounds, such as kaolinite, zeolite, chlorite, and limonite. In the schists which develop

[a] Clarke, F. W., and Hillebrand, W. F., Analyses of rocks and analytical methods: Bull. U. S. Geol. Survey No. 148, 1897, pp. 277–301.

from such sediments these minerals may be altogether absent, their places being largely taken by the micas and other minerals. It is clear that during the metamorphism of the rocks these minerals are taken into solution, and from such solutions the new minerals, containing little water, are deposited. The solution and deposition give the material a less hydrated and more compact form. During the process, at numerous places mica nuclei oriented by the differential stresses (see pp. 671–673) begin to form. The minute nuclei, once formed, serve as cores upon which the material which is continuously taken into solution may be deposited. The mineral particles grow somewhat uniformly, being subject to the same laws in this respect as original particles. (See pp. 120–123.) By studying a series of thin sections from any of the districts in which the rocks of a formation vary from little altered material to coarse schists, all stages of the process may be seen, from that in which the original hydrated minerals are abundant and mica is absent to that in which the former are absent and mica is abundant.

In the foregoing we apparently have the explanation of the large average size of the mineral particles which constitute the schists formed at considerable depth during mass-mechanical action. They are continuous growths during deformation by solution and redeposition.

As excellent illustrations of rocks showing all or many stages of recrystallization of quartz and the development of mica may be cited the schists and gneisses which I have described in the Penokee-Gogebic and Marquette districts of Michigan and in the Black Hills of South Dakota.[a] (Pl. III, *A*, *D*; Pl. XI, *B*, *C*.)

As a beautiful illustration of the transition from finely crystalline to coarsely crystalline rocks may be cited the iron-bearing formation of the Marquette district of Michigan.[b] The deformation of this formation was mainly by recrystallization. In the eastern part of the district granulation and widely spaced fractures occurred to some extent, but the temperature was not high enough for recrystallization, or else some other essential con-

[a] Irving, R. D., and Van Hise, C. R., The Penokee iron-bearing series of Michigan and Wisconsin: Mon. U. S. Geol. Survey, vol. 19, 1892, pp. 305–345. Van Hise, C. R., and Bayley, W. S., The Marquette iron-bearing district of Michigan: Mon. U. S. Geol. Survey, vol. 28, 1897, 444–459. Van Hise, C. R., The pre-Cambrian rocks of the Black Hills: Bull. Geol. Soc. America, vol. 1, 1890, pp. 222–229.

[b] Van Hise and Bayley, cit., Mon. 28, pp. 336–375.

dition was lacking. In the western part of the district, while the rocks were probably not more deeply buried, the deformation was much more profound, and probably because of this the temperature reached 180° C. or more. As a consequence the mineral particles grew to a large size. At places in the eastern part of the district, where the conditions were least favorable for recrystallization, the quartz granules in the jaspilite average about 0.01 mm. in diameter. In the western part of the district, where the conditions were most favorable, the quartz particles in the coarsest jaspilite average about 1 mm. in diameter. Moreover, they show little strain. These particles therefore average about a million times greater than those of the eastern part of the district, and hence to form one new individual the material of a million old particles was utilized. This illustration gives conclusive evidence of the capacity of quartz to accommodate itself to the most intense deformation by recrystallization.

The explanation suggested by Adams[a] for the deformation of the quartz of the leaf gneisses of the original Laurentian district is movement along gliding planes, as advocated by Mügge[b] in reference to ice crystals. However, this explanation is inadequate to explain the phenomena above described, and similar phenomena for other minerals, for two reasons: First, the greater dimensions of the flat new individuals always corresponding to the secondary structures in the slates and schists, are wholly independent of the orientation of the original particles, and therefore independent of their gliding or other definite planes. If gliding had taken place, it must have occurred along definite crystal planes. Second, as shown on pages 686–688, the particles of the metamorphosed schists are very frequently, and in the case of the metamorphosed sediments commonly, much larger than the original particles. In many instances the particles average so much larger that a multitude of old particles are built into a single new particle. In those cases where different mineral particles merge to form new particles of larger size, gliding along any set of definite planes can not possibly explain the process; this can be due only to solution and deposition, or recrystallization, as already explained. But it does not follow from the above that where

[a] Adams, F. D., Report on the geology of a portion of the Laurentian area lying to the north of the Island of Montreal: Ann. Rept. Geol. Surv. Canada for 1895, vol. 8, pt. J, 1897, p. 48.

[b] Mügge, O., Ueber die Plasticität der Eiskrystalle: Neues Jahrbuch für Mineralogie, etc., Jahrgang 1895, vol. 2, p. 212.

recrystallization is the dominant or preponderant process, gliding may not occur as a subordinate simultaneous process, especially with such minerals as calcite, which, as Adams[a] has shown, is especially likely to be deformed by movement along gliding planes.

In the theory of recrystallization we have an explanation of the general uniformity in size of the particles of any definite mineral in a rock metamorphosed at depth during mass-mechanical action: The larger grains of any mineral have smaller areas of contact for the solutions to work on, and therefore granulation plays a large part; the smaller particles have larger areas of contact for the solutions to work on, and consequently recrystallization merges them, producing larger particles. Therefore, the tendency of granulation and recrystallization together is to produce uniform-textured rocks.

Recrystallization lags behind deformation.—In the deep-seated zone adjustment may not lag far behind the disturbing forces. However, in all cases there is apparently some lag. In the most regularly laminated of the schists, close examination usually reveals a slight undulatory extinction, and therefore a state of unequal strain in the minerals, showing that recrystallization has not exactly kept pace with deformation, or else that the schists have been somewhat deformed since recrystallization.

Where such subsequent deformation has not taken place, the amount of strain shadows and granulation is thought in many cases to be a measure of the amount that molecular readjustment lags behind the disturbing movement. In the typical schists strain is in many cases scarcely perceptible. In other cases all of the mineral particles show marked strain shadows. In still other cases the strain shadows are accompanied by more or less of granulation, and this phase of the rocks grades into the ordinary granulated rocks. Thus there are all gradations between molecular readjustment or recrystallization almost pari passu with deformation, and readjustment almost wholly by granulation.

Evidence that recrystallization does nearly keep pace with deformation in the case of the schists consists partly in the absence of marked strain structures, for it is to be supposed that if recrystallization did not nearly keep pace with deformation the result would be that the mineral particles

[a] Adams, F. D., and Nicolson, J. T., An experimental investigation into the flow of marble: Philos. Trans. Royal Soc. London, ser. A, vol. 195, 1901, pp. 363–401.

would show important strain shadows or even granulation. The texture characteristic of the schists (described on pp. 688–690) is itself further evidence of continuous recrystallization during deformation. It is a texture peculiar to the schists. If the minerals were not readjusted in a continuous fashion they must have become granulated by the mechanical forces. If they had become fused into a magma, from that state the material would have recrystallized with textures peculiar to the igneous rocks. The regular arrangement of the mineral particles, with their longer axes in definite planes is just what would be expected if the contained water were taking material into solution and depositing it largely at the borders of the mineral particles, and thus continuously building them out laterally.

Further evidence that recrystallization may nearly keep pace with deformation is found in the porphyritic minerals which frequently occur in the schists Some of the more common of these minerals (mentioned on page 700) are garnet, staurolite, andalusite, feldspar, hornblende, chloritoid, chlorite, and mica. Such porphyritic minerals ordinarily show no perceptible strain. They frequently lie with their longer axes or readiest cleavage across the schistosity. This is true even of mica and chloritoid, the cleavage of the porphyritic constituents cutting directly across the cleavage of the abundant small individuals of mica which accord with the schistosity. It is maintained (p. 702) that such minerals have developed mainly under static conditions after mass movement ceased. These porphyritic minerals seem to be evidence that the differential stresses of static conditions are ordinarily not sufficient to control the orientation of the mineral particles; that in order to do this the differential stresses must be sufficient to produce actual movement throughout the mass of the rocks. If this be so we must suppose that the orientation of the minerals producing schistosity occurred during the movement itself, or, in other words, that recrystallization nearly kept pace with the movements.

During movement, in some cases the tendency for large individuals to grow at the expense of smaller ones may control, and properly oriented individuals grow to a porphyritic size. For instance, porphyritic feldspars may show a marked tendency toward crystallographic orientation, the cleavages of the feldspars corresponding with the cleavages of the rocks.

This is beautifully illustrated by the albite-gneiss of Hoosac Mountain,[a] by augen-gneiss of the French Broad River, and at various other localities.

The argument that orientation of mineral particles in rocks is primarily due to unequal stress in different directions during crystallization applies equally to the cases of the parallel crystallographic orientation of individuals which occasionally occur in rocks crystallizing directly from magmas. Feldspar is not infrequently oriented in such rocks, and the phenomena is known in reference to other minerals.

Conclusion.—From the foregoing it is concluded that the development of the schists is to be explained as a process of chemical action induced by mechanical action, resulting in the constant solution and deposition of the material, or its recrystallization, so as to accommodate it to the changing form of the mass.

ALTERATIONS UNDER MASS-STATIC CONDITIONS.

It has just been shown that metasomatic recrystallization largely induced by mass-mechanical action is the most important process in the development of the schists. However, recrystallization may and does take place under mass-static conditions, by means of which minerals are produced characteristic of the zone of anamorphism. The cause for recrystallization under mass-static conditions is the demand of the pressure for less volume. If the minerals be recrystallized or made over into those which have a higher average specific gravity, the volume is lessened and work is done. Changes are likely to be important in proportion as the temperature is high and the pressure great. It naturally follows that recrystallization under mass-static conditions is important where the rocks are very deeply buried, or where orogenic movements have occurred, or where igneous rocks have been intruded, and especially where two or all of these are combined. If a rock has recrystallized during mass-mechanical action or igneous intrusion, and therefore has developed into a schist, under succeeding mass-static conditions recrystallization is particularly likely to recur, for the orogenic movement or the intrusive produces a higher temperature in the rocks than would obtain at the same depth under static conditions.

---

[a] Pumpelly, Raphael, Wolff, J. E., and Dale, T. Nelson, Geology of the Green Mountains in Massachusetts: Mon. U. S. Geol. Survey, vol. 23, 1894, pp. 59–63.

Under mass-static conditions the textures which are produced by recrystallization are very different from those formed by crystallization during mass-mechanical action. It has been seen that under mass-mechanical conditions schists form, the distinctive textures of which are uniformity of size of the mineral particles, and especially the similar orientation of certain minerals. Under mass-static conditions, where the pressure conditions approximate to hydrostatic, schists do not ordinarily develop. The rearrangement takes place so as to form more condensed molecules, without producing either uniformity of size or regularity of arrangement of the mineral particles. During the development of the mineral particles they ordinarily interfere with one another and interlock, producing a complex texture often more intricate than that formed by the mutual interference of minerals when crystallizing from a magma.

Commonly, the old mineral particles, if large, break up into a great number of other mineral particles of varying size. If, on the other hand, the original particles are very small, they are apt to coalesce so as to produce larger mineral particles; but usually the magnitude of the resultant mineral particles is not great. To the above extent there is a tendency toward uniformity of size, but it does not go so far as to result in approximate uniformity. Indeed, a very notable characteristic of the texture of rocks recrystallized under mass-static conditions is the unequal size of the mineral particles. This results from the fact that there is no movement to prevent the full operation of the law of growth of large individuals at the expense of small ones. In this particular the conditions contrast with those of mass-mechanical action in which large individuals are especially exposed to strain and rupture, and are therefore likely to be destroyed.

This process of the growth of large individuals at the expense of small ones develops a porphyritic texture. This process is of such significance that it needs to be especially considered, as does also another process closely allied to it, that of the regeneration or rejuvenation of old mineral particles of large size which are adapted to their environment.

DEVELOPMENT OF PORPHYRITIC TEXTURES.

Where the mass-static conditions favorable to recrystallization continue long, some of the mineral particles may grow to great size as compared with their fellows, and thus a porphyritic texture is produced. The pressure

conditions demand diminution of volume, and the large mineral particles are apt to be those of high specific gravity. The more important dense porphyritic minerals are feldspar, garnet, staurolite, tourmaline, andalusite, sillimanite, cyanite, mica, chloritoid, and hornblende. The minerals also exhibit a marked crystal habit, and not infrequently as they grow they maintain crystal forms. Often the porphyritic minerals show a distinct zonal texture, comparable in every way to the zonal texture sometimes shown by minerals in igneous rocks. The zonal texture is frequently seen in minerals having a varying composition, as, for instance, garnet; and is rare or has not been observed in minerals having a rather definite chemical composition, as, for instance, staurolite. It is believed that the zonal texture of the minerals is often due to varying composition, during their growth, of the mineral solutions or adjacent minerals, or both. In some cases there may have been actual cessation of growth and later a renewed growth. In such instances the renewed growth is analogous to the process of enlargement of fragmental mineral particles.

Single porphyritic individuals may be larger than hundreds of individuals of the background. Those a centimeter in diameter are very abundant, while those two or even several centimeters in diameter are not infrequent, and occasionally they are many centimeters across.

As the large porphyritic individuals form at the expense of many small mineral particles, they either absorb the material of which the surrounding minerals are composed, and thus grow by their destruction, or else absorb a part and inclose a part. The minerals mentioned differ in capacity to absorb the other minerals which before occupied the space they now occupy. In proportion as they lack capacity to absorb the constituents of prior minerals, they have the capacity to grow around and inclose them, so that a single individual may be a large, reticulating, honeycombed mass, which incloses a large amount of other material. (Pl. III, *C.*) In some cases the inclosed material may be several times as great in quantity as the host. As minerals conspicuous for their capacity to include other minerals may be mentioned andalusite and staurolite; occupying an intermediate position are garnet and feldspar; while tourmaline usually does not contain any considerable quantity of the prior minerals.

A large variety of minerals may be included by the porphyritic constituents, but the dominant inclusion is quartz. Andalusite and garnet are

A

B

A. PARALLEL VEINS OF CALCITE, GREAT BASIN. *B*. BIOTITIC GRANITE SHOWING GARNET SURROUNDED BY LENTICULAR AREAS DEFICIENT IN IRON-BEARING MINERALS.

orthosilicates; staurolite and tourmaline are subsilicates. They are therefore unable to absorb a large amount of silica, and hence the explanation of the abundant inclusions of quartz. The inclusion of quartz is finely illustrated by some of the garnetiferous and staurolitic schists. In the staurolites the quartz frequently seems as abundant as in the background, but the micas and other minerals are usually absent, although they may be abundant in the background. The garnet and staurolite have partly or wholly absorbed the micas, chlorites, feldspars, and other minerals, which are largely composed of the same elements as themselves, and have built them into their bodies, thus making denser minerals.

The evidence of this consists in the absence of inclusions of the iron-bearing constituents of the schists in garnet and staurolite, and the presence of abundant quartzose particles. While frequently the iron-bearing minerals extend without apparent diminution in amount to the garnets and staurolites, in some cases around the garnets are aureoles or lenticular areas of material which are markedly deficient in the iron-bearing minerals. This I first observed at Bristol, Conn. (See Pl. II, *B*.) Here is a biotitic granite blotched by white spots, consisting of quartz and feldspar with no mica, the larger of them 2 cm. wide by 8 cm. long, in the cores of which are large crystals of garnet The same thing is beautifully illustrated by the almandite in a mica-schist of Hampshire County, Mass. The acid minerals, such as quartz and feldspar, outside or inside the garnets which could not be absorbed have arrangements characteristic of the schists.

The above occurrences give beautiful illustrations of the principle of the development of the large heavy mineral particles from the material of small and light ones. They also give positive evidence that the work is done by solution and redeposition. The transportation of the material of a mica flake to a garnet or staurolite must be done by solutions

Commonly the porphyritic minerals do not show any orientation. But in the schistose rocks containing porphyritic minerals it is usually true that the minerals constituting the background have laminar forms, and often similar crystallographic orientation. These minerals of the background often stop abruptly at the junction with the garnets, staurolites, tourmalines, etc., without any deviation whatever or tendency to peripheral arrangement about the porphyritic minerals. The micas may be seen with perfect arrangements extending to the exact junction of the porphyritic

individuals with undiminished transverse dimensions, but with various fractions of the average length of those of the background which have not been interfered with by the porphyritic minerals. In short, the appearance, so far as the minerals of the background are concerned, is precisely that which would be produced if one could cut out from a fully developed schist an outline for a porphyritic mineral and subsequently insert that mineral with extreme nicety. (Pl. III, *D.*)

The minerals included in the porphyritic individuals have the same appearance, and have their granules arranged according to the same system, as the like minerals in the background of the schist.

Where in the schists the porphyritic constituents have crystal habits, and are not arranged with their greater dimensions parallel with the schistosity of the groundmass, the evidence seems conclusive that such porphyritic crystals developed under mass-static conditions. The case seems especially conclusive when readily cleavable porphyritic minerals, such as mica, chlorite, and chloritoid, in well-defined crystals, occur with their cleavages diagonal or perpendicular to the dimensional arrangement and cleavage of similar minerals of the background. Such cases are beautifully illustrated by the Hudson schist of New York and by the Michigamme schist of the Upper Huronian of the Lake Superior region. Such porphyritic constituents with random orientation formed after the movement ceased during which the minerals with parallel orientation were formed and the schistose structure developed.

The conditions favorable to the development of porphyritic crystals are those already mentioned as favorable to recrystallization under mass-static conditions, viz, the presence of water, high pressure, and high temperature. Where those conditions obtain to an exceptional degree porphyritic constituents are common. These conditions are likely to obtain to an unusual degree after either powerful orogenic movements or great batholithic intrusions, or, still more commonly, the two combined. This is illustrated by the porphyritic crystals of nearly every variety, including mica, chloritoid, andalusite, garnet, staurolite, and tourmaline, in the schists adjacent to the great Black Hills[a] granite batholith, and by the many

[a] Van Hise, C. R., The pre-Cambrian rocks of the Black Hills: Bull. Geol. Soc. America, vol. 1, 1890, pp. 222–230.

PLATE III

PLATE III.

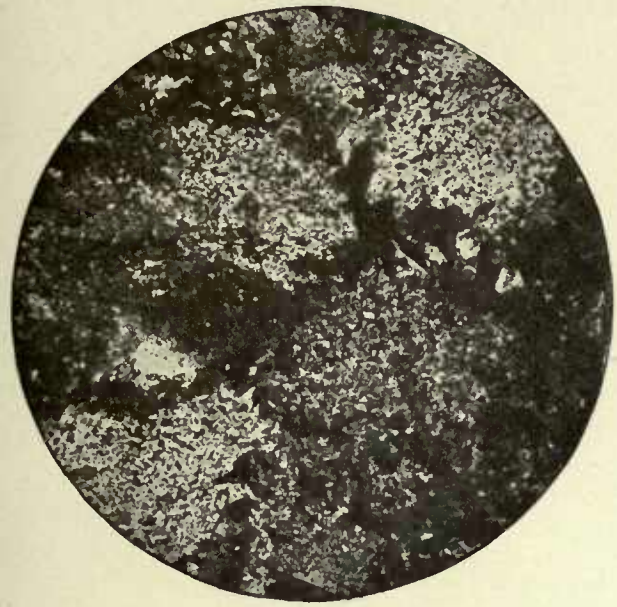
PHOTOMICROGRAPHS OF METAMORPHIC TEXTURES.

A. Uneven texture developed by metasomatic alteration of feldspar to quartz and mica. From biotite-slate of Penokee-Gogebic district, Michigan.

B. Thin section of mashed quartz-porphyry, showing the quartzes elongated by recrystallization, while the adjacent feldspar is little affected. After Futterer.

C. Albite-schist, showing secondary porphyritic albites which include other mineral constituents of the rock and their longer axes parallel to the prevailing schistosity. From Hoosac Mountain, Massachusetts. After Leith.

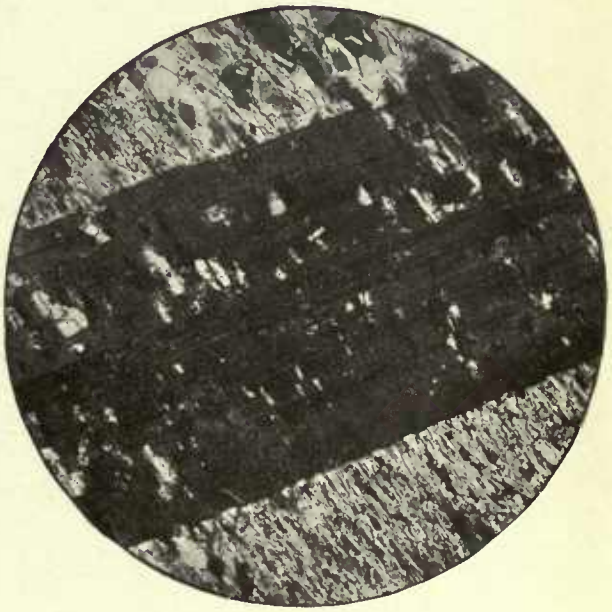
D. Porphyritic chloritoid developed after rock flowage has ceased. The chloritoid includes the other constituents of the rocks with their longer diameters parallel to the prevailing cleavage. From Black Hills, South Dakota. After Leith.



A

B

C



D

PHOTOMICROGRAPHS OF METAMORPHIC TEXTURES.

porphyritic constituents in the schists and gneisses adjacent to the great granite batholiths of western Massachusetts.[a]

Occasionally there may be present in schistose rocks porphyritic minerals which show a marked tendency toward similar crystallographic or dimensional orientation, or both.

To instances of orientation of porphyritic constituents the arguments above given in reference to the usual development of porphyritic minerals under mass-static conditions after movement has ceased are not applicable. This case is discussed on pages 687–688.

REGENERATION OF MINERAL PARTICLES.

The regeneration[b] or rejuvenation in the zone of anamorphism of large mineral particles which have been partly altered in the belt of weathering or the belt of cementation is closely analogous to the growth of porphyritic minerals. Such partly destroyed large minerals are sometimes regenerated at the expense of the small ones for the same reason that the porphyritic minerals form. As an illustration of the process, the feldspars may be cited. In the belt of weathering they are likely to become cloudy in consequence of kaolinization, development of chlorite, zeolite, deposition of iron oxide, etc. In the belt of cementation they may become cloudy, in consequence of zeolitization or other alterations. When such altered feldspars pass into the lower zone the reactions may be reversed; new feldspar is produced, which is controlled in its orientation by the residual unaltered feldspar; the alteration products are absorbed by this new feldspar or else dissolved; thus the cloudy appearance disappears, and the feldspar once more becomes clear and fresh—i. e., is regenerated or rejuvenated.

This process of regeneration is especially likely to occur where the rocks pass from the zone of katamorphism into the zone of anamorphism

[a] Emerson, B. K., Porphyritic and gneissoid granites in Massachusetts: Bull. Geol. Soc. America, vol. 1, 1890, pp. 559–561.

[b] Wolff, J. E., Metamorphism of clastic feldspar in conglomerate-schist: Bull. Mus. Com. Zool. Harvard College, whole ser., vol. 16, 1891, pp. 173–183. Weidman, S., A contribution to the geology of the pre-Cambrian igneous rocks of the Fox River Valley, Wisconsin: Bull. Wisconsin Geol. and Nat. Hist. Surv., No. III, 1898, pp. 20–24. Whittle, C. L., Some dynamic and metasomatic phenomena in a metamorphic conglomerate in the Green Mountains: Bull. Geol. Soc. America, vol. 4, 1893, pp. 155–164. Hobbs, W. H., Phases in the metamorphism of the schists of southern Berkshire: Bull. Geol. Soc. America, vol. 4, 1893, pp. 167–178.

by burying without orogenic movement. Where recrystallization during orogenic movements occurs the process of rejuvenation is less likely to take place, but may occur in the more resistant minerals which escape destruction. As is well known, feldspar is one of the most resistant minerals under deep-seated conditions of deformation, and hence many of the original partly altered particles of this mineral may be rejuvenated during the time in which other minerals are recrystallized. Of course, if the deformation is severe the borders of the original feldspars are likely to be granulated or recrystallized, and during extreme orogenic movements there may be complete recrystallization of the feldspar.

The facts that under certain conditions feldspars are destroyed by kaolinization, chloritization, zeolitization, etc., and under other conditions are rejuvenated or newly developed, have been known for some time. We can now assign reasons for the reversal of these reactions. Feldspar is not adapted to the zone of katamorphism, and especially to the belt of weathering, and it is destroyed by the reactions demanded by the chemical and physical forces there obtaining; whereas feldspar is adapted to the zone of anamorphism, and the chemical and physical forces there at work reproduce it.

The nature of the process of rejuvenation has been illustrated by feldspar because this is the best known case, but other minerals may be rejuvenated in a similar manner.[a]

---

[a] Lepsius has anticipated a number of the points of the previous pages, as is shown by the following quotations and summary from the Geologie von Attika (Ein Beitrag zur Lehre vom Metamorphismus der Gesteine), Dietrich Reimer, Berlin, 1893, 196 pp. With tables and atlas.

"Die Mineralien in den Gesteinen können nur umkrystallisiert werden, wenn ihre Moleküle flüssig werden; dies kann auf dreierlei Weise geschehen:

1. Durch Schmelzung in der Glühhitze und zwar für unsern Fall bei Gegenwart von Druck, also durch die eben besprochene Druckschmelze.

2. Durch Lösungsmittel auf chemischem Wege, und zwar in unsrem Falle bei Gegenwart von Druck und bei einer Temperatur, die höher ist als die mittlere Temperatur der Erdoberfläche, die jedoch im allgemeinen nur bis zu einigen hundert Grad Celsius und wohl nicht über 500° steigen wird.

3. Durch hohen Druck auf mechanischem Wege, das ist diejenige Art von Druckverflüssigung, welche durch die Springschen Versuche illustriert wurde.

Betrachten wir jetzt die zweite Möglichkeit, die Verflüssingung der Moleküle durch Lösungsmittel auf chemischem Wege; diese Art der Verflüssigung und Auskrystallisierung aus der chemischen Lösung scheint mir am besten die von aus beobachteten Vorgänge bei der Metamorphose der Gesteine aufzuklären." (P. 183.)

Holds that the schistose Silurian and Tertiary rocks when metamorphosed were buried to a depth of about 12,500 meters, which with a specific gravity of 2.5 would give a pressure of 3,125 atmospheres. (P. 187.)

IGNEOUS WORK.

The igneous work of the zone of anamorphism is comprised under "Injection."

INJECTION.

Injection in the zone of anamorphism probably occurs on a much greater scale than in the zone of katamorphism. The field evidence for this view is found in the vast amount of intrusive igneous material in the areas where deep denudation has exposed rocks which have been within the zone of anamorphism. For instance, in the extensive areas of the Canadian pre-Cambrian, in the Paleozoic of New England, and in the cores of the great mountain masses of the world intrusive rocks constitute a large percentage of the total material exposed. Indeed, over considerable districts intrusive igneous material composes 25 to 50 per cent of the area. These facts accord with what one would expect, for as magma struggles toward the surface the quantity which is unable to accomplish the task naturally increases from the surface toward the source.

Holds that recrystallization takes place, producing coarser crystals, because of the fact that the larger crystals have less surface for action than the small crystals, and therefore that, if solution and precipitation are occurring, the small crystals will be dissolved and the large crystals grow. (P. 188.)

Holds that where the pressure is great the chemical reactions will take place in such a sense as to produce a diminution of volume, and cites Caillete and Pfaff's work as showing that certain reactions can be greatly hindered and finally ceased altogether by a pressure of from 40 to 80 atmospheres. (P. 190.)

Holds that crystallization is not possible without solution, and explains that through crystallization under pressure the large crystals grow at the expense of the small ones. In this connection states, "ist dieser zweite Krystall kleiner als der erste, so kann er nach dem oben angeführten Gesetze aufgelöst werden, und können alsdann seine Moleküle allmählich mittels des Lösungwassers zu dem grösseren Krystall hinüberwandern." (P. 193.)

"Neben der Zeitbauer sind die für die Grösse der Krystalle bestimmenden Faktoren: die Höhe der Temperatur, mittelbar die Stärke des Druckes, sowie natürlich auch die grössere oder geringere Löslichkeit der Mineralien in überhitztem Wasser und die absolute Quantität, in welcher die betreffenden Moleküle in dem ursprünglichen Sedimente vorhanden waren. Daher wächst die Grösse der Krystalle auch mit dem stärkeren Druck; jedoch geschieht überhaupt kaum eine Umkrystallisierung, wenn ein mechanischer Druck allein ohne chemische Lösung wirken sollte; umgekehrt wird die Lösungsfähigkeit des Wassers erhöht durch den Druck." (P. 193.)

"Bei der Entstehung von metamorphen Gesteinen wirken also vier Ursachen zusammen: Wasser als chemisches Lösungsmittel der in den Gesteinen vorhandenen Substanzen; höhere Temperatur, um das Wasser zu erwärmen; mechanischer Druck, um das überhitzte Wasser in flüssiger Form in den Gesteinen festzuhalten und dessen Lösungsfähigkeit zu erhöhen; endlich auch eine lange Zeitdauer, während welcher die chemischen Umsätze in den Gesteinen vor sich gehen können." (P. 194.)

MANNER OF INTRUSION.

The manner of intrusion in the zone of anamorphism differs in many respects from that in the zone of katamorphism. In the latter zone it has been explained that the igneous rocks mainly follow fractures. In the lower zone no large fractures can be supposed to exist continuously. In some way the magma must make its way through rocks which normally have no large openings.

The progress of the igneous rocks is therefore a matter of far greater difficulty. In consequence of earth movements the material may make its way (1) en masse, without breaking across the structures of the intruded rocks to a great extent; (2) by breaking across the structures of the intruded rocks and by following along planes of weakness such as cleavage, bedding, and contacts; and (3) by fusion and absorption of the intruded material.

(1) It is probable, indeed certain, that all three of the above processes occur to some extent, but it is believed that the movements en masse, without extensive breaking across the intruded rocks, are of great consequence. As evidence of this may be cited the fact that in general, adjacent to the great batholiths, the injected rocks have peripheral structures, as if they had been driven aside en masse by the earth stresses in connection with epeiorogenic and orogenic movements. It is believed that the magmas transmit the thrusts they receive substantially under the laws of hydrostatics, and consequently make their way by raising up and pushing aside the material previously occupying the space, without necessarily breaking through it on a large scale. Under such circumstances, if the intruded rock be sedimentary, the bedding of the sediment is peripheral to that of the great intrusive masses. Materials of other kinds are similarly arranged. The intrusive acts in reference to the rocks as would a hemispherical or lenticular mass raised against a piece of flexible but tightly stretched leather. The leather roughly adjusts itself to the shape of the hemisphere or lenticule.

Also, as will be seen, high pressure, temperature, and water result in the recrystallization of the rocks adjacent to intrusive masses, and during this process they are shortened in a direction normal to the intrusion and sometimes lengthened in a direction peripheral to it. Thus room is made for the entering mass. Often the result, so far as the relations of the

masses are concerned, is as if a solid body were pushed up against a sheet of rubber. The rubber would be thinned and extended above the mass and on the sides. Therefore a consequence of recrystallization is to carry the entering magma nearer to the surface.

The deep-seated intrusives, producing uplift of the intruded rocks, form mountains at the surface. Such mountains have been called subtuberant by Russell and others.[a] When later erosion removes the capping rocks the igneous masses below are seen. Intrusive igneous masses of this class are exposed on a great scale in this country, in the Cordilleras, in the Black Hills, northwest of Lake Superior in Canada, and in New England. The intrusive masses may be nearly spherical, lenticular, or many times longer than broad. The larger of them have minor diameters of many kilometers and major diameters of 50 to 100 kilometers, or even more. When the magnitude of these masses is appreciated it is easy to understand how the great interior earth stresses result in concentrated upward motion at some area, as a consequence of which the magma, either liquid or potentially liquid, slowly but with tremendous power oozes up toward the surface, carrying with it and pushing aside the superincumbent rocks.

(2) Next in importance to raising the intruded rocks and pushing them aside in the lower zone is the breaking across or the following of the structures or planes of weakness of the intruded mass. During the great movements resulting in mass intrusion the rocks which are thrust aside are cut and injected parallel to their structures on a large scale, as a necessary correlative of the greater process above described. Returning to the illustration of the leather, this material stretched against a hemisphere is wrinkled on its sides unless it be as extensible as rubber. Similarly, as a great mass of igneous rock is intruded and pushes the rocks up and aside, they are wrinkled, unless we assume greater flexibility than is warranted by the facts. Commonly, therefore, subtuberant intrusion demands close corrugation on the sides. Further, I have held in another place that great periods of intrusion are also periods of rapid orogenic movements.[b]

When the deformation of a rock mass is rapid, fractures may extend much deeper into the earth than they would under normal conditions.

---

[a] Russell, I. C., Volcanoes of North America, Macmillan Co., New York, 1897, pp. 103–105. Also, On the nature of igneous intrusions: Jour. Geol., vol. 4, 1896, p. 189.

[b] Van Hise, C. R., Earth movements: Trans. Wisconsin Acad. Sci., Arts, and Letters, vol. 11, 1898, pp. 493–494.

(See pp. 658–658.) I have said that it is characteristic of the zone of flowage that no large openings can be supposed to exist *continuously*. It does not therefore follow that at times of rapid movement extensive fractures may not be temporarily formed. If these were at a place of subtuberant intrusion, or were adjacent to any magma, material would break away from the central mass, intrude itself into the openings and fractures, wedge the walls apart, and thus we should have intrusives for a considerable belt peripheral to the central mass which are analogous in their forms to the intrusives characteristic of the belt of cementation—that is, intrusives along fractures; and this would be so even if the rock alterations of the place were, on the average, those characteristic of the zone of anamorphism rather than of the zone of katamorphism. We have here really the case of an intermediate belt of combined fracture and flowage, fractures extending deep at times of rapid deformation, although the normal conditions are those of flowage. Thus from the great central masses of igneous rocks smaller masses extend in various directions to various distances, some being subordinate subtuberant masses, and others taking advantage of the temporary fractures and thus forming dikes There is a marked tendency for these subordinate masses to follow planes of weakness, as, for instance, the contacts between rocks of different character, the bedding of sedimentary rocks, or other structures such as the planes of cleavage in schistose rocks. Intrusives of this kind usually have greater dimensions parallel to the structures followed than in the transverse directions. The tendency of the injections to follow cleavage is very marked indeed. Parallel to the planes of cleavage in the slaty and schistose rocks intrusions may be very close together and small, there being perhaps a considerable number within the breadth of an inch; or the intrusives along cleavage planes may be larger and far apart, or they may be any combination of these. All these phenomena are well illustrated by the Hudson schist of New York City, especially at New Rochelle, and by the gneisses at many places upon the Piedmont Plateau.

(3) Finally, the upward progress of the great masses of magma is also doubtless made in part by the fusion and absorption of the material with which it is in contact, although the evidence that such absorption has taken place on a great scale is lacking. That absorption does take place in a minor way, however, is certain. (See "Fusion and absorption," pp. 728–736.)

RESULTANT METAMORPHISM.

It is natural to expect that the rocks surrounding great batholiths of igneous rocks, and those intimately associated with the abundant and numerous branch batholiths and dikes, would be profoundly modified, and such is the fact. Conditions for profound and far-reaching modification are perhaps most favorable in connection with batholithic injection and conjoint orogenic movements, and to this fact is probably due the classification of certain kinds of metamorphism as contact metamorphism. But it must be remembered that, with the one exception, the forces and agents at work are essentially the same as those in other parts of the zone of anamorphism, the difference being, merely, that under the conditions of batholithic intrusion these forces and agents are particularly potent. During an intrusion the orogenic forces and the thrust transmitted by the magma both act upon the rocks, and thus the mechanical processes are at work. The temperature is abnormally high; hence the solutions are especially potent. To some extent, as pointed out on page 662, the magma itself may furnish water, and thus the surrounding rocks contain more than an average amount of water; and this is the most important agent in recrystallization. Therefore about great batholiths are usually zones of profound metamorphism.

FACTORS CONTROLLING METAMORPHISM.

The factors of alteration to be especially considered in this connection are the size of the intrusive masses, the temperature, the amount of water present, and the composition of the intrusive and intruded rocks.

SIZE OF INTRUSIVE MASSES.

The size of the intrusive masses is of the first importance in the amount of metamorphism. The smaller of the deep-seated irregular masses are ordinarily called stocks; those of intermediate size, bosses; and those of the largest size, batholiths. We know of no downward limit for any of these. Oftentimes they undoubtedly increase very rapidly in magnitude with depth, although this fact can not be directly observed. Erosion may have extended only deep enough to expose a very small area of a batholith, and yet for long distances about that place the subtuberant mass may be only a short distance below the surface, and the rocks exposed therefore be well within the limit of its influence. This must be a common case, for it

is certain that the batholiths of great magnitude which now show a large area must at an earlier stage of erosion have been in the position just described with reference to the surrounding rock. Therefore, while metamorphism is a function of the size of the intrusive masses, it is not a function of the size of the masses exposed. When the masses are small and do not rapidly expand in size below, the appreciable metamorphic effect may extend only a few centimeters or a few meters; but the metamorphosing effect of the great batholiths, some of them scores of kilometers in diameter, may extend from a kilometer to many kilometers.

THE TEMPERATURE.

The temperature effect depends largely upon the size of the intrusive mass, and to a less extent upon its temperature. The greater the size of the intrusive mass and the higher its temperature the larger the amount of heat it is able to furnish to the surrounding rocks and the farther that heat penetrates by conduction and convection. In the matter of heat the intrusives in the zone of anamorphism are in a vastly more advantageous position than those of the belt of cementation. In the latter belt the rocks are comparatively near the surface. There is a somewhat rapid circulation of the water, so that the heat is dispersed, slowly to be sure, but with relative speed as compared with the zone below; but in the zone of anamorphism the great store of heat of an intrusive mass is so far below the surface, and the circulation is so slow, that it is a sustained factor in increasing the temperature of the surrounding rocks, certainly for geological epochs, and frequently in the case of the larger masses for geological periods. Thus there is ample time during high temperature for the alterations to take place. Moreover, the heat through conduction and convection slowly disperses itself from the central mass over a very wide area and produces a metamorphic effect upon the rocks far beyond the distance to which the materials of the magma can possibly penetrate.

AMOUNT OF WATER PRESENT.

The amount of water, as fully explained in other connections (see pp. 741–748), is of the utmost importance in determining whether the metamorphism is by granulation or by recrystallization. In proportion as water is abundant recrystallization is likely to take place. Where the intrusive

masses are introduced into sedimentary, volcanic, or other rocks, which have passed through the zone of katamorphism, they already contain a reservoir of water in hydrated minerals which can be released by dehydration. This supply is usually ample to entirely recrystallize the rocks. But as nearly as we can ascertain from observation, the magmas themselves contain a considerable store of water, as pointed out on page 662. At the time of crystallization of a magma a portion of this water escapes and passes slowly into the surrounding rocks, and thus in magmas we have a second reservoir, which supplements the first; so that adjacent to masses of igneous material in the zone of anamorphism there is commonly an amount of water such that recrystallization readily takes place.

COMPOSITION OF INTRUSIVE AND INTRUDED ROCKS.

The absolute and relative compositions of the intrusive and the intruded rocks are both of importance in reference to the alterations which take place. So far as observation can determine, it seems to be a fact that the alterations are more widespread in connection with batholiths of granite and syenite and other acid rocks than with basic rocks. Possibly the apparently greater contact effect may not be due so much to the chemical composition of the crystallized intrusive as to a greater than average amount of occluded water (see pp. 720–728), and to the high temperatures which are frequent accompaniments of acid magmas.

The character of the intruded rock has much to do with the nature of the alteration. In so far as rocks are composed of minerals which are easily recrystallized, this process is more likely to take place; whereas rocks which are difficult to recrystallize under the same conditions may be comparatively little altered. The presence of hydrous minerals which may be dehydrated and furnish water, and fineness of grain are very favorable to recrystallization.

As to the mutual effect upon the chemical composition of the intrusive and the intruded rocks, the law in the zone of anamorphism is the same as that in the belt of cementation, viz, that the joint endomorphic and exomorphic effect is to make the intruded and intrusive rocks approach each other in composition. Under the law of mass action each gains from the other elements in which it is deficient. One of the commonest illustrations of this law is furnished by the large amounts of feldspar which frequently

develop in a schist adjacent to an intrusive, when the continuations of the schist formations remote from the intrusive contain little or no feldspar. Such are the facts about the Black Hills batholiths (see p. 724) and at many places about the New England granite batholiths.

Another excellent illustration is furnished by the Rib Hill quartzites of central Wisconsin, adjacent to a great intrusive batholith of augite-syenite. The center of the quartzite mass contains no feldspar. As the masses of syenite are approached feldspar and hornblende appear in the quartzite. These minerals increase in amount as the syenite is approached, and close to that rock the quartzite is so thoroughly impregnated with feldspar which has developed in and between the grains as to make many of the hand specimens of the rock difficult to discriminate from a granite.

There is much difference between the zones of anamorphism and katamorphism in the extent to which interchange of material takes place between the injected and the injecting rocks. It has been seen that in the belt of cementation, in consequence of the porosity of that zone, the material of the magma, both by direct injection and by transmission through water, may profoundly affect the average chemical composition of the intruded rock for great distances from the intrusive mass. While these changes do not take place on an extensive scale to any such distance from the intrusive in the zone of anamorphism, we must not go too far in minimizing the importance of the exomorphic effect of intrusive rocks in this zone. The short distance to which magma can furnish material to the injected rock is compensated to a large extent by the great scale of the intrusions. As has been explained, there are in the zone of anamorphism innumerable batholiths, bosses, and stocks, and in temporary fractures intimate intrusions for extensive areas. Hence the conditions favorable for endomorphic and exomorphic effects without transportation of material to a great distance from an intrusive are widespread and important. The quantity of solutions is small, and they make their way very slowly through the subcapillary openings. The consequence is that, where there is a great simple mass of intrusive with few offshoots, the chemical compositions of the two rocks are affected for only a short distance from each other; but where the intrusive and intruded rocks are intimately mingled there may be a profound modification in the chemical composition of both rocks over an extensive area, each approaching the chemical composition of the other. This general statement requires some amplification.

As just noted, where the contacts are sharp one does not need to go far in order to obtain rocks the chemical composition of which corresponds to that of the intruded and intrusive masses, although the intrusive may be affected to a greater distance by the absorbed material than are the intruded rocks, since in a magma the elements are more rapidly distributed than they are in the solid rock, in which the water is very small in amount and moves very slowly. However, even in the case of the intruding magma, Becker[a] and others have shown that the process of diffusion is comparatively slow, a very long time being required for the chemical composition of the intrusive to become greatly affected at a considerable distance from the contact with the intruded rock.

Where, however, the intruded and intrusive rocks are intimately mingled there may be profound modification of the chemical composition of both rocks. A case of this already given is that of parallel injection into slates, schists, and gneisses. In such a case the modification may be so great that the chemical composition of the intruded rock, if sedimentary, may vary greatly from that of ordinary sediments, and the intruded rock may differ considerably in composition from the main mass of intrusives. Such rocks as these are the so-called injection gneisses (See pp. 725–727.) These rocks are usually coarsely or finely banded, and may be aqueous and igneous in any proportion, or igneous rocks of two kinds in any proportion, provided the intruded rock was a schistose igneous one.

Another case of intimate mingling of the two rocks is that where numerous fragments of the intruded rock are caught by the intrusive. By subsequent movement such fragments may make their way into the magma for some distance from its border, and their partial or complete absorption may affect the chemical and mineral composition of the intrusive for considerable or even long distances from the outside of the intrusive.

In closing this part of the subject it should be noted that the above statements as to the rather short distances to which chemical changes are usually limited does not contradict the statement already made, and more fully developed later, that the metamorphic effect of great intrusives often extends far from the intrusive masses.

---

[a] Becker, George F., Some queries on rock differentiation: Am. Jour. Sci., 4th ser., vol. 3, 1897, pp. 27–31.

METAMORPHIC EFFECTS.

The metamorphic effects accomplished in connection with intrusions are both structural and mineral. It has already been noted (p. 712) that the effects of great masses of intrusive rocks may extend for several or many kilometers. It is by the study of areas adjacent to batholiths that the contact effects are best appreciated. About a great batholith there are commonly various zones of metamorphism which grade into one another. This is true both of the structures which are formed and of the minerals which develop.

STRUCTURES.

It has already been indicated that as batholiths are intruded the rocks are deformed by being pushed aside. The deformation is mainly accomplished by recrystallization, as described on pages 690–696. During the process the majority of rocks take on a slaty or schistose structure. Cleavage developing normal to the pressure is peripheral to the batholith or circumscribes it. The contact effect naturally dies out as the distance increases from the intrusive. Near the intrusive the recrystallized rock may be a coarse-grained gneiss or schist; farther away from the intrusive it may become an ordinary slate; and still farther away a slaty cleavage may not be found unless it had been previously developed in some other way. Between these three zones there are gradations.

In America peripheral structures in gneisses, schists, and slates are illustrated by the Carboniferous batholiths of New England, described by Emerson;[a] by the Algonkian batholiths of the region northwest of Lake Superior, described by Lawson;[b] by the granite batholith of the Black Hills, described by Van Hise;[c] and by the batholiths of Vancouver, described by Dawson.[d]

If a previous regional cleavage exists in an area intruded by a batholith, this older cleavage is reenforced if it correspond to the new direction of cleavage, and tends to be obliterated if it be diagonal or perpendicular

[a] Emerson, B. K., Porphyritic and gneissoid granites in Massachusetts: Bull. Geol. Soc. America, vol. 1, 1890, pp. 559–561.

[b] Lawson, A. C., The laccolitic sills of the northwest coast of Lake Superior: Bull. Geol. and Nat. Hist. Surv. Minnesota, No. 8, 1893, pt. 2, pp. 24–48.

[c] Van Hise, C. R., The pre-Cambrian rocks of the Black Hills: Bull. Geol. Soc. America, vol. 1, 1890, pp. 206–212.

[d] Dawson, George M., Report on a geological examination of the northern part of Vancouver Island and adjacent coasts: Rept. Geol. and Nat. Hist. Surv. Canada for 1886, pt. B, 1887, pp. 1–129.

to it. All of the above relations may obtain about a single batholith, as in the case of the Black Hills granite already mentioned. At places where the new cleavage develops at right angles to the old cleavage, the older may be completely obliterated near the batholith. Farther away from it the old and new cleavage may both be present and intersect each other, and still farther away the old cleavage may be dominant.[a]

THE MINERALS.

The minerals which form depend upon the intensity of the metamorphism. To illustrate, closest to the Black Hills granite batholith is a gneiss containing abundant quartz, mica, feldspar, garnet, staurolite, hornblende, and tourmaline. Farther from the granite is a schist containing quartz and mica, comprising both muscovite and biotite, with staurolite and garnet. Farther out is a schist in which the staurolite is absent and garnet is present. Still farther away is an ordinary slate in which there are small flakes of mica, but in which there are no garnets or staurolite. Similar illustrations are furnished by the batholiths of Massachusetts, described by Emerson;[b] but these have, in addition to the minerals above mentioned adjacent to the granite, cyanite; somewhat farther out in the schists, sillimanite; and still more remote in the ordinary slate, andalusite. The three minerals mentioned furnish a particularly good illustration of the metamorphic effect with reference to position, since they have precisely the same chemical composition. Also these minerals furnish a perfect illustration of the principle, expounded in Chapter IV (pp. 182–186), that in proportion as the metamorphic effect is profound and the pressure great, minerals of high specific gravity develop. The specific gravities of andalusite, sillimanite, and cyanite are, respectively, 3.18, 3.235, and 3.615, and this is their order observed in approaching the intrusives.

In a given case the different mineral zones are not sharply defined, but grade into one another. Moreover, the most intensely metamorphosed area may contain all the minerals developed by the feebler metamorphic processes This may be explained on the supposition that as the metamorphic wave passes away from the central batholith the conditions were first those of mild metamorphism, later those of moderate metamorphism, and finally those of severe metamorphism. Also adjacent to the

[a] Van Hise, cit., pp. 232–234. [b] Emerson, cit., pp. 559–561.

intrusive mass as it cools, following the severe metamorphism, the conditions are those of moderate and mild metamorphism. As the metamorphic wave passes out from the newly intruded batholith the minerals first developed may later be transformed into other minerals requiring more intense metamorphic power, and thus early minerals may be partly or wholly obliterated by transformation into the minerals of more intense metamorphism. Under such circumstances the facts might be discovered by partial change or by pseudomorphs. The phenomena are finely illustrated about the batholiths of western Massachusetts. According to Emerson—

The zonal character of the contact metamorphosis around these batholites is interesting, especially in aluminous sediments. The first wave of heat develops the easily formed minerals, fibrolite and chiastolite; stronger heat, staurolite and garnet; then the first influx of the alkaline waters from the granite forms pseudomorphs of these in muscovite, and with increasing heat feldspars develop. So the highly altered rocks nearest the intrusive mass have often passed through all the stages one passes over in going from the outer zone inward. Thus, in the Carboniferous argillite in Harvard one finds masses of interlaced prisms of andalusite, of the largest size and finest pink color, inclosing crystals of fibrolite in abundance (the two not orientated to each other), and the whole in every stage of change to coarse muscovite. This preserves three stages which were plainly passed over in succession, and nearer the granite large feldspars are interspersed. In the Hatfield argillite, a zone of delicate chiastolite is succeeded inwardly by a zone where the chiastolites are changed to a mixture of muscovite and minute twins of staurolite (the mass still retaining the shape and black cross of the chiastolite) by the influence of greater heat and alkaline solutions; and nearer the granite the whole changes to sericite schist, chlorite schist, and finally hornblende and feldspar appear near the contact with the hornblende granite.[a]

In Europe at many localities a zonal arrangement of the metamorphic minerals peripheral to intrusive masses has been observed. The minerals commonly developed and the order of their arrangement are in general similar to the instances above given. Four well-known instances are those furnished by the Vosges, the Erzgebirge, the Hartz, and the Tyrol. In the Vosges, granite intrudes the Steiger Schiefer.[b] Says Rosenbusch:

Die gesammte Contactzone der Steiger Schiefer an den Granititen lässt sich demnach gemäss der wesentlichsten Entwicklungsglieder in 3 annähernd concentrische Partialzonen zerlegen, welche etwa zu bezeichnen wären als:

(1) die Zone der Fleck-, Frucht- oder Knotenschiefer mit unveränderter Schiefergrundmasse oder *Knotenthonschiefer;*

[a] Emerson, B. K., Porphyritic and gneissoid granites in Massachusetts: Bull. Geol. Soc. America, vol. 1, 1890, pp. 560–561.

[b] Rosenbusch, H., Die Steiger Schiefer und ihre Contactzone an den Granititen von Barr-Andlau und Hohwald, R. Schultz & Co., Strassburg, 1877, pp. 178–250.

(2) die Zone der Fleck-, Frucht- oder Knotenschiefer mit deutlich gröber krystallin entwickelter Schiefergrundmasse oder *Knotenglimmerschiefer;*

(3) die Zone der *Hornfelse*, speciell der weitaus vorwiegenden *Andalusithornfelse.*[a]

In the Erzgebirge granite intrudes phyllite. Dalmar summarizes as follows:

Sonach lassen sich also innerhalb der fortschreitenden Reihe von Umwandlungen, welche die Phyllite im Contact mit den Granitstöcken erlitten haben, folgende vier Stadien unterscheiden:

(1) Das Stadium der *Fruchtschiefer* mit *unveränderter Schiefermasse.*

(2) Das Stadium der *Fruchtschiefer* mit *krystallinisch veränderter Schiefermasse.*

(3) Das Stadium der *schieferigen Glimmerfelse.*

(4) Das Stadium der *Andalusitglimmerfelse und Andalusithornfelse.*[b]

In the Hartz granite has intruded the sedimentary rocks, and here Lossen finds three contact zones. Says Lossen:

Im Allgemeinen aber doch sehr wohl ausgeprägte, concentrisch um den Granit verlaufende Steigerungszonen der nach dem Eruptivgestein hinwachsenden Umbildung: die Aeussere Knotenschieferzone, die mittlere Hornfelszone und die innere Zone der Glimmerschiefer-ähnlichen Hornfelse gegliedert werden.[c]

Near Monzoni in the Predazzo district of Tyrol is a set of zones characterized in passing from the intrusive by a succession of garnet, augite, serpentine, and brucite.[d] This is a very interesting case, because the first two minerals are those which ordinarily develop in the zone of anamorphism, whereas the third and fourth minerals commonly develop in the zone of katamorphism. So far as I know this is unique. It suggests, if all these minerals be original, that near the intrusive mass the pressure was sufficient to require reactions giving decrease in volume, and therefore the conditions were those of the zone of anamorphism; whereas at a greater distance the pressure was not so great but that reactions could take place with increase of volume, and therefore the conditions were those of the zone of katamorphism. However, before this can be regarded as established it must be shown that the serpentine and brucite developed simultaneously with the garnet and augite, and are not later alteration products.

---

[a] Rosenbusch, cit., pp. 177–178.

[b] Dalmer, K., Erläuterungen zur geologischen Specialkarte des Königreichs Sachsen: Section Kirchberg: Leipzig, 1884, Blatt 125, pp. 26–27.

[c] Lossen, K. A., Erläuterungen zur geologischen Specialkarte von Preussen und den Thüringischen Staaten: Blatt Harzgerode, Berlin, 1882, p. 45.

[d] Teller, F., and John, C. von, Geologisch-petrographische Beiträge zur Kenntniss der dioritischen Gesteine von Klausen in Südtyrol: Jahrbuch k.-k. geol. Reichsanstalt, 1882, XXXII, 589–684. Irving, A., Metamorphism of rocks: Longmans, Green & Co., London, 1889, p. 80.

One additional American illustration is given. Grant describes the development of contact minerals adjacent to the great basal gabbro of northeastern Minnesota.[a] This is an interesting case, since the intrusive rock is basic and since it is in contact with several different formations—Animikie slates, Animikie iron-bearing member, green-schists, greenstones, and granites. The prominent contact minerals developed in the slates are feldspar, biotite, and muscovite, with occasional graphite, cordierite, and hypersthene. The important contact minerals in the iron-bearing member are magnetite, amphibole, augite, hypersthene, and olivine. In the metamorphosed greenstones augite and hypersthene are found in considerable amounts. Besides the distinctive minerals developed, all of the rocks are completely recrystallized for a distance varying from a hundred meters to several hundred meters from the intrusive rock.

Concluding this part of the subject, it is evident that the development of the metamorphic minerals occurs largely while intrusion is taking place and movement is still going on, which explains the marked tendency for the development of slates, schists, and gneisses. Following the intrusions of the great batholiths and the orogenic movements connected with them the mass conditions are static, yet the conditions may be very favorable for recrystallization. The temperature may still be high and the solutions active, and under such circumstances the conditions are very favorable for the development of porphyritic crystals which have no relation in their orientation either to the batholiths or to the slates, schists, or gneisses. Hence it follows that within these rocks peripheral to the batholiths we find the best illustrations of secondary porphyritic crystals. Moreover, the porphyritic crystals which appear are dependent upon the intensity of the metamorphism. The order of the heavy porphyritic crystals in relation to the batholiths is that above mentioned, viz., near the batholiths are apt to be the heavy silicates, tourmaline, staurolite, and cyanite; more remote from them, garnet and sillimanite; and still more remote, andalusite. Of course these overlap and are intermingled, as already explained.

PEGMATITES.

The complex processes in connection with the intrusive batholiths and their offshoots may, and indeed do, produce masses of rocks which

[a] Grant, U. S., Contact metamorphism of basic igneous rock: Bull. Geol. Soc. America, vol. 11, 1900, pp. 503–510.

may be called pegmatites. So far as my observation goes, many of the more complex phenomena of pegmatization which can not be explained by igneous injection alone are in regions in which the rocks have been buried to a very considerable depth. They commonly form in the lower part of the zone of fracture, in the zone of combined fracture and flowage, or in the part of the zone of flowage in which continuous fractures may exist temporarily The phenomena occur to a great extent in the lower zone in connection with offshoots from the deep-seated batholiths—i. e., injection dikes which have made their way along planes of rock weakness, such as contacts or cleavage planes. Probably a strictly logical arrangement would require that the treatment of pegmatites be deferred until the relations of the zones of anamorphism and katamorphism are considered, but the relations of pegmatites to deep-seated intrusives are so close that, for the sake of continuity, the subject is dealt with here.

Pegmatization has been variously explained as the result of true igneous injection, of aqueo-igneous action, and of water impregnation or cementation. Brögger has strongly enforced the idea that many pegmatite veins are true igneous injections.[a] In support of this idea he cites the undoubted frequent association of pegmatitic veins with intrusive masses of acid rock, the fact that many of the pegmatitic veins behave like other eruptives, and that their structure is that of igneous rocks.

Williams is in substantial agreement with Brögger in assigning an essentially eruptive origin for the greater number of the pegmatite dikes of the Piedmont Plateau.[b] In favor of this view he cites (1) the likeness in chemical and mineralogical composition of the granite masses to the pegmatites, although it is stated that the pegmatites are usually somewhat more acid; (2) the fact that the size and abundance of pegmatites are directly proportional to their nearness to eruptive granite masses; (3) that in composition the pegmatites are independent of the rocks which surround them, and (4) that they do not show the drusy or symmetrical character of veins. While Williams thus holds to the igneous origin of the pegmatites, he thinks they show a greater activity of mineralizing agencies than the normal granite. In conclusion of his discussion, he says: "The writer therefore

[a] Brögger, W. C., Syenitpegmatitgänge der südnorwegischen Augit-und Nephelinsyenite: Zeitsch. für Kryst., vol. 16, 1890, pp. 215–235.

[b] Williams, G. H., The general relations of the granitic rocks in the middle Atlantic Piedmont Plateau: Fifteenth Ann. Rept., U. S. Geol. Survey, 1895, pp. 675–684.

interprets those pegmatites which by their mode of occurrence and association strongly indicate an igneous character as the products of the residual and therefore most acid portion of a granite magma highly charged with water and other mineralizing agents. Such a siliceous material, in a state intermediate between fusion and solution, has been injected into fissures and there crystallized into very coarse-grained aggregates, not necessarily through any great slowness of this process, but rather in virtue of the aid to crystallization afforded by the abundance of mineralizers present."[a]

While Williams and Brögger strongly emphasize the igneous side of pegmatization, they both agree that some of the pegmatites which show a comb structure are essentially the result of aqueous processes.[b]

Standing at the other extreme is Hunt, who maintains a strictly aqueous origin for pegmatites.[c] In an intermediate position, ascribing an aqueo-igneous origin to pegmatites, are Élie de Beaumont, Scheerer, Lehmann, Credner, Reyer, and Crosby and Fuller. Scheerer in 1847, according to Hunt, "Conceives the congealing granitic rocks to have been impregnated with 'a juice,' which was nothing else than a highly heated aqueous solution of certain mineral matters. This, under great pressure, oozed out, penetrating even the stratified rocks in contact with the granite, filling cavities and fissures in the latter, and depositing therein crystals of quartz and of hornblende, the arrangement of which shows them to have been of successive growth."[d] Reyer, following Scheerer, regards the pegmatites as "Exsudate der erstarrenden Granitmasse."[e] But of all the authors writing upon pegmatites Lehmann,[f] followed by Crosby,[g] makes the closest approximation to the view which I hold in reference to pegmatites. Lehmann conceives that as a result of crystallization of the parent mass and the concentration of the water in the residual uncrystallized part, a gelatinous magma rich in silica is formed. "Between such a gelatinous magma and a saturated aqueous solution a large number of consecutive intermediate stages can be imagined."[h] However, Lehmann insists that no part of the

[a] Williams, G. H., The general relations of the granitic rocks in the middle Atlantic Piedmont Plateau: Fifteenth Ann. Rept. U. S. Geol. Survey, 1895, p. 684.

[b] Williams, cit., p. 679.

[c] Hunt, T. Sterry, Chemical and geological essays: Osgood & Co., Boston, 1875, pp. 191–219.

[d] Hunt, cit., p. 189.

[e] Reyer, E., Theoretische Geologie: Schweizerbart'sche Verlagshandlung, Stuttgart, 1888, p. 101.

[f] Lehmann, Johannes, Untersuchungen über die Entstehung der altkrystallinischen Schiefergesteine: Bonn, 1884, pp. 24–58.

[g] Crosby, W. O., and Fuller, M. L., Origin of pegmatite: Tech. Quar. vol. 9, 1896, pp. 326–356.

[h] Crosby, W. O., and Fuller, M. L., citing Lehmann, cit., p. 345.

water is atmospheric, but is wholly eruptive water. Crosby and Fuller, however, think it is possible that a portion of the water required "for the more perfect hydration and liquefaction of the residuum of the magma may be derived from extraneous sources."[a]

It seems to me that to explain adequately all the facts of pegmatization described in various regions of the world, we must conclude that all three processes have been at work—in some cases igneous injection, in some cases aqueo-igneous action, in other cases pure water cementation, and in still other cases combinations of two or all of these processes. It is further believed that there is no sharp separation between these processes, but that, on the contrary, there are all gradations between the three. That is, it is thought highly probable that, *under sufficient pressure and at a high temperature, there are all gradations between heated waters containing mineral material in solution and magma containing water in solution. In other words, under proper conditions water and liquid rock are miscible in all proportions.* This possibility, first published by me in 1896,[b] in precisely the above words, has received almost conclusive experimental verification at the hands of Barus. As noted on page 80, Barus has shown that at temperatures below 200° C., and at high pressure, soft glass and water are actually miscible in all proportions.

From the water solutions true cementation takes place; from the rock solutions, true injection. Pegmatization comprises these and the intermediate processes. It is not to be expected that under great pressure and at high temperatures there is any sharp line of demarcation between the processes of aqueous cementation and igneous injection. At the surface it is usually easy to sharply separate aqueous from igneous action, but deeper within the earth even the strongest rocks are latently plastic. At great pressure heated waters must have power to absorb a quantity of material far beyond that at the surface of the earth. Truly liquid rock is highly impregnated with water. It therefore is probable that at considerable depths we have, on the one hand, material which all would call water solution, and on the other hand material which all would call liquid rock, with no sharp division line between the two. If this be so, there are all

[a] Crosby, W. O., and Fuller, M. L., Origin of pegmatite: Tech. Quar., vol. 9, 1896, p. 348.

[b] Van Hise, C. R., Principles of North American pre-Cambrian geology: Sixteenth Ann. Rept. U. S. Geol. Survey, 1894–95, pt. 1, 1896, p. 687.

stages of gradation between true igneous injection and aqueous cementation, and all the various phases of pegmatization may thus be fully explained.

This idea of continuity was first suggested to me by the phenomena observed in the schistose rocks surrounding the intrusive core of the Black Hills. Remote from the intrusives the sedimentary rocks are slates; adjacent to it they are schists and gneisses. The core rock is a great batholith of granite, 11 km. broad and 18 km. long. Besides this central mass there are, to the southwest, a number of smaller masses, from 2 to 6 km. long, which may be connected below with the greater mass. From the central mass great quartz-feldspar dikes radiate. In passing away from the core the dikes become smaller and have a less typical form; at the same time the material assumes the appearance which we ordinarily denominate pegmatitic. These veins might be considered true igneous injections. Still farther away the pegmatitic masses begin to have vein-like characters—that is, there is a rough concentration of the material in different layers parallel to the walls. Still farther away a true banded-vein structure is found. Yet farther away feldspar becomes less and less important in the veins and the quartz more abundant, until remote from the granite the impregnating material is mainly quartz. Within the intruded rock, adjacent to the granite, there is also an extensive development of feldspar, giving the rock a banded appearance and changing it from a schist to a gneiss. If one examined only the outer zone, in which the quartz cementation series occur, one would not doubt that they are ordinary deposits from ground water; if one examined the dike-like masses of the inner zone adjacent to the great granite mass, one would not doubt that they are true igneous injections; but in passing back and forth between the two, one observes that there is every gradation between them, and is driven to the conclusion that true igneous injection was predominant adjacent to the granite, that in the central zone aqueous and igneous agencies were about equally important, and that in the outer zone aqueous agencies were predominant. It is impossible to believe that the larger dikes—plainly offshoots of the central batholith—are not igneous injections; it is equally impossible to believe that quartz veins remote from the granite are dikes, or that the ordinary granite magma has penetrated to considerable distances between the individual grains of the schist and thus impregnated it with feldspar.

From the foregoing it is clear that under the general term pegmatite

are included the results of three somewhat distinct phases of action, which, however, grade into one another; first, pegmatization mainly aqueous; second, pegmatization mainly igneous, and third, aqueo-igneous pegmatization.

The first case is illustrated in the Marquette district of the Lake Superior region,[a] where at certain places in the Michigamme formation there is a great development of feldspar within the interstices of the schists. In the crevices minute pegmatitic veins of quartz and feldspar occur. No adjacent intrusive in this formation has been discovered even by the closest detailed study. In this case it seems clear that pegmatization has taken place during the metamorphism of the rocks, in connection with mechanical action, without the assistance of any extraneous igneous material, and is therefore essentially aqueous.

The second of these cases is illustrated by the pegmatites described by Brögger in southern Norway,[b] in which igneous injection satisfactorily explains all the phenomena. It is to be noticed that in this region the process of pegmatization occurred at a maximum depth of 600 meters, while much of it occurred at a depth varying from 30 to 100 meters.

The third phase of pegmatization, which combines both aqueous and igneous agencies, is far the most extended and important. By it are formed the great class of the rocks which are usually spoken of as pegmatized. This phase may affect massive igneous rocks, massive sedimentary rocks, and their metamorphic equivalents. It occurs in both acid and basic rocks. In all, the effects may be most complex, ranging from the formation of great pegmatite dikes to the development of individual crystals of feldspar, quartz, and other minerals anywhere within the intruded masses.

But this phase of pegmatization is most extensive and best illustrated by rocks in which there is a gneissic or schistic structure, since, as pointed out on page 710, cleavage furnishes planes of weakness which are readily taken advantage of by the igneous rocks. The relations are best studied where intrusive and intruded rocks are of different colors; for instance, where there is a dark-colored schist intruded by granite. In such rocks will be seen a background of schist. Parallel to the folia are innumerable

[a] Van Hise, C. R., and Bayley, W. S., The Marquette iron-bearing district of Michigan: Mon. U. S. Geol. Survey, vol. 28, 1897, pp. 447–448.

[b] Brögger, W. C., Syenitpegmatitgänge der südnorwegischen Augit- und Nephelinsyenite: Zeitsch. für Kryst., vol. 16, 1890, pp. 215–235.

cementation-injection bands of lighter color. These bands vary from those as thin as leaflets, being perhaps but a single row of crystals, to those of considerable width. There may be many such bands within the space of a centimeter, or a single one may be many meters across. Frequently parts of the injected material are in dike-like masses of varying size, which cut the schistosity at various angles. At numberless places the leaf-like bands of pegmatitic-looking material parallel to the schistosity are found to be connected directly with the dike-like masses cutting the schistosity.

The dark schistose bands are found to show exomorphism in various degrees by the injecting material. Besides recrystallization, the modification consists in the development of various new minerals, the material of which is derived in part at least from the intrusive. Clear evidence of this is the frequent addition of minerals, or a large increase in the amount of minerals, in the pegmatized rock of the kinds found in the adjacent intrusive. Not only may the main mass of unpegmatized schist show a deficiency of certain minerals as compared with the pegmatized areas, but if within the pegmatized area there be any considerable belt of schist not affected by the pegmatite masses it may exhibit a similar deficiency. The endomorphic effect upon the injection bands follows the same rule. The more intimate the intrusion and pegmatization the greater the endomorphism. The smaller bands of injection material gain proportionally more material from the schist than do the larger ones.

The intrusive rock, which is the final inciting cause of the third phase of pegmatization may vary from acid to basic, but pegmatization in connection with granite and other acid intrusives has been most closely studied. The process of granitization described by Michel Lévy[a] comprises the particular form of pegmatization produced by this rock. The pegmatization known as granitization has been studied more closely than other forms because of its prevalence, because the light color of the granite renders it easily distinguishable, and perhaps because acid magmas supply more water and heat than basic ones.

It seems to me that the third phase of pegmatization described above can be conceived of only as an aqueo-igneous process. In many instances the larger masses of cutting material are truly igneous dikes containing a

[a] Lévy, A. Michel, Sur l'origine des terrains cristallins primitifs; Congrès géologique international, 4th sess., London, 1888, pp. 117–129.

little water. On the other hand, the intimate penetration of all parts of the rocks, down to the openings between the mineral particles, by the pegmatizing material can be accomplished only by very mobile solutions which are more nearly allied to water than to magma; but such water is very rich in mineral material. Between these extremes are all gradations.

The aqueo-igneous pegmatites, especially the pegmatitic schists and gneisses, in all their phases may be seen in any of the regions of America in which there are great batholithic intrusions. They are illustrated equally well in the Cordilleras, the Lake Superior region, Canada, and eastern United States from Maine to Alabama. All these regions afford innumerable perfect illustrations of the process. Even the most extreme pegmatization is illustrated at many places. One of the best instances known to me is that of Rib and Mosinee hills, central Wisconsin. These hills of quartz rock are surrounded by a great batholith of augite-syenite many kilometers in diameter. Within the quartz rock adjacent to the syenite feldspar has so extensively developed as to change the rock from a nearly pure quartz rock to one in which feldspar is an important constituent. A more extensive and no less perfect illustration of pegmatization, as well as of almost every other phase of the process, is furnished by the Hudson schist in the upper part of Central Park, New York, and even better at New Rochelle, adjacent to Long Island Sound. Williams's accurate description of the phenomena exhibited in Maryland shows this to be an admirable case of pegmatization.[a]

In summary, pegmatization, when it occurs on a great scale, usually is found in connection with great intrusive masses in which there have been long-continued composite intrusions. No great batholith is the result of a single simple intrusion. The introduction of such masses went on irregularly through a very long time. Pegmatitic masses are not the result of a distinct epoch of eruption, but usually are produced in connection with the closing phases of igneous activity. The pegmatites very frequently cut the igneous rocks intruded in an earlier stage of the igneous epoch. After the main masses of igneous rock have crystallized they continue to contract as they cool, and are thereby fractured. This occurs while they are still very hot, and gives ready access to the pegmatizing material. Also the surround-

[a] Williams, G. H., The general relations of the granitic rocks in the middle Atlantic Piedmont Plateau: Fifteenth Ann. Rept. U. S. Geol. Survey, 1895, pp. 657–684.

ing rocks which have been long affected by the batholiths become highly heated as a result of direct conduction and in consequence of convection through water. The occluded water which undoubtedly exists in the parent mass, at the moment of crystallization is in large measure expelled. As crystallization continues the residual magma gradually becomes more watery. Thus a considerable part of the water, the presence of which is evidenced by the character of the pegmatites, is derived from the magma itself. Doubtless the pegmatite dikes in immediate connection with the great parent masses of igneous material, which closely resemble ordinary igneous dikes, largely and perhaps predominantly derive their water from the igneous rock itself.

As the pegmatites close to the central mass solidify, a large portion of the water is expelled and travels outward to help form the pegmatitic rock having a more distinctive vein character; but in many and perhaps most cases the water in the outlying pegmatite dikes and veins, which more and more assume the character of ordinary veins, has been largely derived from the surrounding rocks. We thus have completely explained the variations from the true igneous dikes by imperceptible gradations to materials which have the unmistakable characters of aqueous mineral veins.

This injection-cementation theory of pegmatization gives an adequate explanation of the extreme coarseness of crystallization which the pegmatites frequently exhibit. The rocks in which the pegmatites form, both the parent crystallized igneous mass and the surrounding rocks, are highly heated, and hence during the closing pegmatitic stages, even if the masses be small, the temperature falls so slowly that there is ample time for the formation of very coarse crystals. Also it is well known that there is no limit to the size to which the crystals may grow from water solutions. The separation of the crystalline material in many pegmatite veins is more nearly analogous to crystallization from a solution than to the solidification of a solvent (see p. 113), and this analogy, so far as it exists, is favorable to very coarse crystals.

FUSION AND ABSORPTION.

In connection with metamorphism in the deep-seated zone where igneous rocks are among the agents, the question of the fusion of the intruded rocks should be considered. It has been held by Mallet and by others that heat produced by mass-mechanical action is a sufficient cause to pro-

duce aqueo-igneous fusion, and that such supposed fused material is the source of molten material for volcanoes.[a] Mallet supposes that the material is mechanically divided so fine that a sufficient amount of heat is developed by this work and by friction between the particles to fuse the rock. However, he does not tell how fine this must be, although he speaks of reducing a rock to an absolute powder. What is meant by an absolute powder is not apparent, but one might suppose it means a powder the particles of which are of molecular size.

The conclusions herein contained concerning recrystallization and rock flowage have an important bearing upon the hypothesis of aqueo-igneous fusion. It has appeared that if water be present when the material, as a result of the mechanical subdivision, or for any other cause, reaches the very moderate temperature of 185° C., the adjustment is accomplished mainly by recrystallization, and that fusion is not necessary to account for the plasticity of the rocks. Probably a much higher temperature is required for aqueo-igneous fusion than for recrystallization. Barus has failed to secure aqueo-igneous fusion of the silicates at a temperature of 600° C.,[b] and at temperatures much lower than this it is certain that recrystallization goes on very rapidly.

So far as the typical schists and gneisses themselves are concerned, it is certain that they are not the products of aqueo-igneous fusion. They have the peculiar textures and structures characteristic of these rocks. (See pp. 779–783.) Every magma crystallizes according to the laws of magmas, and produces textures and structures which are characteristic of such crystallization. The textures and structures of the two classes of rocks are very different. There is no evidence that the great masses of the magmas are formed by the fusion of the crystallized rocks in consequence of mechanical action. But it does not follow that various rocks, including the schists and gneisses, may not be fused by contact with intruded magmas. It has been seen in connection with injection that profound metamorphic effects are produced upon the intruded rocks, the ordinary metamorphic forms being slates, schists, and gneisses. It has been held that the phenomena of pegmatization may be explained by crystallization

[a] Mallet, Robert, Volcanic energy; an attempt to develop its true and cosmical relations: Philos. Trans. Royal Soc. London, vol. 163, 1874, pp. 147–227.

[b] Powell, J. W., Report of the Director: Fourteenth Ann. Rept. U. S. Geol. Survey, pt. 1, 1893, pp. 161–162.

from materials between water solutions and true magmas. During pegmatization, in proportion as the conditions approach those of a magma, the textures and structures may depart from those of slates, schists, and gneisses and approach those of igneous rocks. Thus there may be all gradations between the textures and structures characteristic of the slates, schists, and gneisses and those characteristic of the igneous rocks. In some regions there occur remarkable combinations of textures and structures characteristic of various rocks; for instance, the clastic rocks, the schists, and the igneous rocks.

When once a rock, whether a sediment, a crystallized igneous rock, or a metamorphic rock, has become a magma by fusion, whether it be by aqueo-igneous fusion or by dry fusion, the resultant material is a true magma. The crystallized rock which forms from it by cooling has all the characteristics of an igneous rock. The textures and structures formed are those of the igneous rocks. The textures and structures of the fused sedimentary, original igneous, or metamorphic rocks are totally destroyed, and the newly formed rock is to all intents and purposes a new igneous rock. If rocks derived by the fusion of previous solid rocks have again crystallized on a large scale, it is most difficult to prove this. The contacts between the fused and unfused portions of the material would be similar to those between ordinary intruded and intrusive rocks. The only way which I can suggest to show fusion and recrystallization on a large scale is to prove that the rock supposed to be fused and recrystallized possesses the chemical composition of the rock from which it is believed to have been derived. For instance, a fused and recrystallized shale should possess the textures and structures of an igneous rock, but the essential chemical composition of a sedimentary rock. This criterion of chemical composition as applied to the red granular rock (meta-rhyolite) of Pigeon Point leads to the conclusion that it is probably an independent intrusive, rather than the result of the fusion of the Animikie rocks by the gabbro.[a] (See pp. 732–733.)

But while it has not been shown that fusion and recrystallization have taken place on a great scale, various cases have been described in which the evidence seems clear that to some extent intruded rocks have been fused.

There can be no question that fusion of fragments included within igneous rocks does take place. Very numerous inclusions which are found

[a] Bayley, W. S., The eruptive and sedimentary rocks on Pigeon Point, Minnesota, and their contact phenomena: Bull. U. S. Geol. Survey No. 109, 1893, p. 118.

adjacent to great batholiths show various stages of absorption. Frequently the partly absorbed residual fragments are profoundly metamorphosed, being perhaps completely recrystallized, and frequently greatly changed in chemical composition from that of the parent rock.

It is certain that the absorption of fragments must react upon the chemical composition of the absorbing rock. In so far as rocks fused and absorbed by a magma differ from it in chemical composition, they must change the chemical composition of that magma. Where the rock absorbed is igneous, and therefore has the composition of igneous rocks, the modified magma has a composition intermediate between two magmas. Where the material has the composition of a sediment, this changes the chemical composition of the magma toward that of the sediment. For instance, if a considerable portion of limestone or dolomite be absorbed, the rocks become very rich in calcium or calcium and magnesium. If a considerable portion of shale or slate derived from mudstone be absorbed, the igneous rock would be likely to be deficient in the alkalies, especially sodium; it might be deficient in the alkaline earths; and it would probably be high in aluminum, thus becoming intermediate in chemical composition between igneous rocks and the mudstone series. If a sediment intermediate between the limestone series and the mudstone series, as, for instance, calcareous shale or slate, were absorbed by magma, while there might not be any deficiency in the alkaline earths, there would be a deficiency in the alkalies, and probably the aluminum would be abnormally high.

If a rock were fused by contact with a magma without absorption by it or mingling with it, it would, of course, have approximately the composition of the original solid rock, and therefore that of a sedimentary, igneous, or metamorphic rock, as the case might be. Doubtless the compositions of such rocks would be somewhat modified by the exomorphic effect of the igneous rocks. (See pp. 713–714.) If any considerable mass of solidified rock were fused as a result of contact with igneous rocks, it is natural to suppose that for a zone of variable width the two would become mixed, and thus there would be a gradation in chemical composition between the fused rock and a normal magma.

While it is beyond dispute that all of the above cases occur, petrographers have been inclined to believe that none has taken place on a great scale. It may well be doubted whether the excess of heat in molten magma, beyond that required to keep it liquid, is sufficient to perform the vast

amount of work required for the liquefaction of a great mass of solidified rock. Work must be done in fusing the material, and work must be done in expanding the material. Besides raising the temperature to the fusion point, all the latent heat of fusion must be supplied. The heat required for the process of fusion of rocks in a furnace is very great. Ordinarily a magma has a temperature only slightly in excess of that required to hold it in the liquid form. Therefore, that it could furnish a sufficient amount of heat to liquefy immense masses of solid rocks seems highly improbable. And it has already been seen that it can not be assumed that the necessary heat is furnished by orogenic movements, although this may be a helpful factor.

While fusion of solidified rocks of the lithosphere on a great scale, either by magma or by orogenic movement, or the two combined, is to be proved, it is certain that fusion has locally occurred. One of the clearest instances of fusion or semifusion in America is that on Pigeon Point, described by Bayley.[a] At this place is a metarhyolite, called keratophyre, on one side of which is a great mass of gabbro, and on the other side of which are the slates and quartzites of the Animikie series. The keratophyre has all the characteristics of an eruptive rock younger than the gabbro. In a position between the keratophyre and the gabbro is a coarse-grained red rock, which is intermediate in character between the two and grades into each of them. It is therefore regarded as a product formed by the intermingling of the gabbro and rhyolite magmas, the gabbro having been actually fused for a short distance from the keratophyre. For a distance of about 9.5 kilometers, with a few interruptions, the contact rock has a width of from 30 to 90 meters, and for one continuous stretch of nearly 3 kilometers it has an average width of fully 60 meters. If this rock, which is intermediate in composition between the metarhyolite and the gabbro, and which grades into each, and yet has the textures and structures of an igneous rock, really represents the result of the action of the quartz-keratophyre on the gabbro, as it appears to do, it is one of the best known cases of actual fusion of one rock by another.

Between the metarhyolite and the slates and quartzites of the Animikie there is another contact belt which extends for about the same length as the

[a] Bayley, W. S., The eruptive and sedimentary rocks on Pigeon Point, Minnesota, and their contact phenomena: Bull. U. S. Geol. Survey No. 109, 1893, pp. 1–121.

contact between the quartz-keratophyre and gabbro, and has an even greater width, averaging perhaps 90 meters, and being in some places as wide as 150 meters. But only a comparatively small part of this belt, that nearest the rhyolite, has the textures and structures of an igneous rock, and seems to have been completely fused and recrystallized into slates and quartzites. The fusion metamorphism produced by the metarhyolite is correlated with the enormous masses of intrusive granite which occur in the Keweenawan series above the Animikie. The Pigeon Point dike of this rock doubtless is located at one of the passages through which the material of some of these larger masses made their way toward the surface. In this connection it is notable that subsequent intrusive trap dikes cut all of the other rocks of Pigeon Point with sharp contacts, and no sign of metamorphosing effects.

Bayley states that the metarhyolite itself may be the product of the action of the gabbro upon the slates and quartzites. If this suggestion is correct the Pigeon Point locality is a still more remarkable case of the production of a rock by fusion of sediments. But that the rhyolite has been produced from the slates can not be considered as determined. Indeed, the analyses of the rhyolites and of the slates and quartzites are different from each other in various important respects. While the amount of silica and alumina in the two rocks is substantially the same, the alkalies are nearly twice as abundant in the rhyolite as in the sedimentary rocks. Also, the iron is more than twice as abundant in the sedimentary rocks as in the igneous rocks. Nor can it be supposed that the surplus of alkalies and the deficiency of iron in the rhyolite can be explained by the gabbro, it modifying the composition of the fused slates and quartzites so as to produce a magma of the composition of the rhyolite; for if any considerable portion of gabbro magma had been added the silica content would have fallen and the alumina would have gone up. Furthermore, the gabbro is scarcely richer in alkalies than the slates and quartzites; hence, on the theory that the red rock was formed by the fusion of the slate and quartzite by the gabbro, one would have to explain why the quantity of alkalies in the red rock is about twice as great as in either of its possible sources. Thus the analyses seem to stand in the way of the conclusion that the granular red rock (metarhyolite) is really a result of the fusion of the Animikie slates and quartzites by the gabbro.[a]

[a] Clarke, F. W., and Hillebrand, W. F., Analyses of rocks and analytical methods: Bull. U. S. Geol. Survey No. 148, 1897, pp. 106–110.

Cases of claimed fusion of vastly greater magnitude than that at Pigeon Point are described by Lawson, Barlow, and other members of the Canadian survey. Lawson[a] has held that the great batholithic masses of granite and gneiss, some of them many kilometers in diameter, in the region of Rainy Lake and Lake of the Woods, northwest of Lake Superior, have been produced by the fusion of the sedimentary and volcanic series, which he has called Keewatin and Coutchiching. He has called this a case of subcrustal fusion. Similar statements have been made by Barlow in reference to the batholiths of granite in the Original Huronian district;[b] and the same thing has been said with reference to the granite and gneiss of the Original Laurentian district. However, no adequate evidence has been offered to support any of these conclusions. Composite chemical analyses have not been made of the Keewatin and Coutchiching rocks and the granites and gneisses supposed to be formed by their fusion, in order to compare their compositions and thus to determine whether the granites could possibly have been derived from the Keewatin and Coutchiching rocks by subcrustal fusion. All of the phenomena along the contacts of the granitic rocks and the Keewatin and Coutchiching are such as may be found at various parts of the world where batholiths of igneous rock have intruded other rocks. Many fragments of the intruded rocks are included in the intrusive. At many places there is a border belt in which the two are intermingled in the most confused way, and, furthermore, in the intruded rocks pegmatization has occurred adjacent to the batholith. The phenomena might possibly lead one to infer the derivation of the intrusive rocks from the intruded rocks by the fusion of the latter, and subsequent action as an intrusion of the magma thus formed, but I do not so interpret them.

I have gone over the Rainy Lake and Lake of the Woods region in the field, and have visited and closely studied the specific localities described by Lawson as giving evidence of subcrustal fusion. At every one of these localities the phenomena are precisely those which generally occur where great intrusive batholiths penetrate other rocks. For instance, at the Narrows of Kaiarskons Lake, which is cited by Lawson[c] as one of the best

[a] Lawson, A. C., The internal relations and taxonomy of the Archean of central Canada: Bull. Geol. Soc. America, vol. 4, 1890, pp. 185–186.

[b] Barlow, A. E., Relations of the Laurentian and Huronian rocks north of Lake Huron: Bull Geol. Soc. America, vol 4, 1893, pp. 313–332.

[c] Lawson, A. C., Report on the geology of the Rainy Lake region: Ann. Rept. Geol. and Nat. Hist. Survey of Canada, for 1887–88, new ser., vol. 3, pt. 1, 1889, p. 32.

instances giving evidence of subcrustal fusion, the granite cuts the hornblendic schist in a most intricate fashion. However, in most cases the contacts between the two rocks are knife-like in their sharpness, and this is true whether the granite dikes and veins are large or small. At one place a few feet square the granite and schist are so confused as to make it possible that the hornblende-schists were locally softened. The granite near the contact contains numerous fragments of the schist. The hornblendic schist generally retains its typical texture and structure directly to the contact with the granite. The phenomena are clearly those of complex intrusion, with no evidence whatever that the granite has crystallized from the fused hornblendic schist. Similar phenomena were found at other localities cited by Lawson as evidence of subcrustal fusion.

This case has been dwelt upon because it is the one in America where it has been most strongly claimed that immense masses of igneous rocks have been produced by the fusion of older solidified rocks. The relations seem to me, however, to be clearly those which are characteristic of great batholithic intrusions in the rocks of the zone of anamorphism.

Another instance where in America it has been claimed that fusion metamorphism has taken place on a great scale is that described by Emerson. It is well known that in eastern Massachusetts there are numerous great batholiths of granite intrusive in the Paleozoic strata. Concerning these batholiths Emerson makes substantially the following statements:

The Quincy granites of eastern Massachusetts do not alter the Cambrian schists and do not absorb any material from them. Several other granite bands extending across Worcester County contrast with the Quincy band in the following particulars: They are often coarsely porphyritic, while the Quincy granites are not. They are microcline granites. The Quincy granites are orthoclase granites. They contain biotite, or biotite and muscovite instead of biotite and hornblende or glaucophane.

These granite batholiths are also contrasted with the Quincy rock in having a broad peripheral layer, which has all the peculiarities of pegmatite in some cases, and grades into black albitic granites, or even quartz-diorites.

These differences are largely due to the fact that in the Worcester district the granites have fused much of the surrounding schist into their composition. This was proved by finding characteristic inclusions of the schist in great numbers and of every size in the granite, and also by tracing these inclusions into smaller and smaller filaments, until they faded from sight, and finding with the microscope far beyond this point in the fresh granite clear traces of the schists. Where the schist contains pyrite, garnet, fibrolite, cordierite, or graphite, the granite becomes more ferruginous and garnetiferous. The amber coarse fibrolite of the schist appears dissolved and

recrystallized as a white, silky bucholzite, or fazer-kiesel in the granite, and the graphite scales are inclosed in all the constituents of the granite over many square miles.

Over the whole surface of the great Hubbardston batholith of perfect coarse porphyritic granite, 51 kilometers long and 10 kilometers wide, it was possible to map the areas once occupied by the different schists, which formerly mantled over the granite mass, by means of the indestructible constituents of the former schists, by the portions which had melted into the mass of the granite, by the filaments still remaining unabsorbed, and by the different aspect of the granite, dependent largely upon the great increment of iron. Using the first two criteria especially, this double mapping of the region was carried out in the sheets prepared for the United States Geological Survey.

The region extending for several kilometers south from Mount Wachusett, and that north and south of Brookfield, in the Hubbardston batholith, furnish abundant exposures for the study of the phenomena here described.[a]

The statement of facts which Emerson makes seems clearly to lead to the conclusion that the granites of the Worcester district have actually fused the metamorphosed schists to some extent. However, the changes in chemical and mineral character of the granites adjacent to the schists may be partly due to the transfer of material from the injected rock by solutions. Until the facts for this district are given in detail, including chemical analyses of the different phases of the granites, it will be impossible to say how far the intruded schists have been absorbed by the granite; and certainly the assumption that the differences between the Worcester granites and the Quincy granites are due to absorption of schistose material by the former requires much more evidence than has yet been offered.

COMBINATIONS AND RELATIONS OF THE VARIOUS PROCESSES.

The processes of welding, strain within the elastic limit, strain beyond the elastic limit, cementation, metasomatism, and injection rarely occur separately. Commonly several of them take place at the same time, and in many instances all of them unite in the metamorphism of a rock. In the previous pages, for the sake of clearness in analysis, each process has been considered by itself, so far as this was possible, so that the effect of each could be clearly appreciated. This natural tendency to consider each process separately, and the tendency to regard a certain process under consideration as the sole cause of metamorphism, have led to the artificial classification into dynamic metamorphism, contact metamorphism, etc

[a] Emerson, B. K., Difference in batholithic granites according to depth of erosion: Bull. Geol. Soc. America, vol. 10, 1899, pp. 499–500.

The mechanical process of welding can not take place without strain within the elastic limit. Strain beyond the elastic limit can not occur without strain within the elastic limit and welding. Therefore, where the former occurs all the mechanical processes are involved. The chemical processes of cementation and metasomatism do not occur separately; where one takes place the other is sure to be active. These processes, together, go on with or without injection. But injection, which involves both mechanical and chemical factors, never takes place without involving one or two or all of the other processes. Where it takes place on a large scale it is sure to include all the mechanical processes. Moreover, under such circumstances the exomorphic alterations involve the chemical transformations of cementation and metasomatism on a great scale.

From the foregoing it follows that in most instances of alteration in the zone of anamorphism it is impracticable to state the relative importance of the mechanical processes among themselves or of the chemical processes among themselves. However, the chemical processes, as a group, and the mechanical processes, as a group, can be better compared. As has been noted, the mechanical processes where important usually produce granulation, and the chemical processes where important result in recrystallization; but also mechanical action promotes chemical action. The importance of the relations of these two classes of processes demands full consideration.

RELATIONS OF GRANULATION AND RECRYSTALLIZATION.

In a rock the same mineral may be partly granulated and partly recrystallized. Even the individual grains of a mineral may exhibit the two processes in various proportions. In this case the fracturing may be along the borders of the individuals, may extend entirely across them, or may granulate them throughout. The simultaneous solutions and depositions may occur along the borders of the original or the secondary granules, or within the spaces produced by the fracturing, or may regenerate the old mineral particles throughout. Any of the deposited material may occur as independent individuals or as enlargements of original grains or mechanical granules. Thus, in the different particles of the same mineral in a given rock granulation or recrystallization may be the dominant process. If this be so, the same is true, to an even greater extent, of the particles of different minerals.

Whether granulation or recrystallization is preponderant in a given place in the zone of anamorphism depends upon many factors. Some of these factors are, the character of the material and water content, temperature, pressure, and rapidity of deformation.

CHARACTER OF MATERIAL.

The degree to which granulation and recrystallization takes place depends to a considerable extent upon the character of the material. The character of the material involves both mineral composition and coarseness.

In the same rock mass certain minerals may be mainly recrystallized and others mainly granulated or even retain their integrity. For instance, it is well known that quartz suffers granulation and recrystallization much more readily than feldspar. This is illustrated by the recrystallization of the flat individuals of quartz in the quartz-porphyry described by Futterer[a] (Pl. III, *B*), in which the feldspars have been little affected.

I shall make no attempt to compare the various minerals with one another with reference to ease of recrystallization. There are all gradations, from calcite, which can be easily recrystallized in the laboratory by the passage of water through finely powdered material under very moderate pressure, to the more refractory minerals, such as feldspar.

Since some minerals when strained recrystallize much more readily than other minerals, it follows that a formation composed chiefly of one class of minerals may be deformed mainly by granulation, and an adjacent formation composed of another set of minerals may be deformed mainly by recrystallization. One formation may thus show complete granulation or other important strain effects, while the recrystallization of the adjacent formation, because of the greater mobility of its mineral particles, nearly keeps pace with the deformation. One rock may recrystallize so as to show the textures and structures of the schists and gneisses with more or less residual strain effects, while an interlaminated rock recrystallizes so readily as to take on a granolitic texture after movement has ceased. As an illustration of this are the closely associated gneisses and marbles of the Adirondacks and of the Hastings series of Canada. The gneisses, besides having their characteristic textures and structures, show marked residual strain, while at

[a] Futterer, Karl, Die "Ganggranite" von Grosssachsen, und die Quartzporphyre von Thal im Thüringer Wald, Heidelberg, 1890, pp. 27–47.

various localities interstratified with these are coarse marbles with granolitic textures showing no other strain effects than those of polysynthetic twinning and similar phenomena, which may have been developed by the slight stresses to which the material was subjected in section cutting in the laboratory.

The coarser the particles the more likely is granulation to be of importance. The finer the particles the more likely is recrystallization to be dominant. The finer the particles originally or by granulation the greater is the surface exposed to the action of the solutions. The dissolving power of water, when not nearly saturated, is almost directly in proportion to the area upon which it can act. If the grains of a rock be broken by granulation into particles having radii 0.1 of those of the original grains, each small grain will have 0.001 the volume of an original grain, and the total surfaces of the fewer original grains will be to the total surfaces of the more numerous grains as 1 : 10. If the granulation goes so far as to give the granules radii averaging only 0.01 of those of the original grains, each small grain will have 0.000001 of the volume of the original grains, and the total surfaces of the original grains will be to the total surfaces of the granules as 1 : 100. A good illustration of mechanical granulation is furnished by the anorthosites described by Adams.[a] Mr. S. H. Ball has compared the size of the grains of the original anorthosite and the granulated anorthosite in two specimens, the result showing that, on the average, the ratio of the diameters of the feldspar grains of the original rock to the diameter of the granulated grains is 1 : 40, or one feldspar grain of the original rock is broken into about 64,000 grains.

Ultimately, even under conditions otherwise favorable to granulation, finer subdivision does not continue, for so large a surface is exposed to the action of the solutions that the process of adjustment is accomplished by recrystallization at least to such an extent that the granules do not, on the average, decrease in size. In this fact of increased surface of action for the solutions by granulation we have the explanation of the fact that granulation is not known to produce particles the average of which is near the limit of observation with a moderate power of the microscope.

An excellent example of the influence of the character of the material

---

[a] Adams, F. D., Report on the geology of a portion of the Laurentian area lying to the north of the Island of Montreal: Ann. Rept. Geol. Surv. Canada, new ser., vol. 8, 1895, pt. J, pp. 85–134.

upon the gradation and relations between granulation and recrystallization is furnished by the Algonkian rocks of the Black Hills.[a] There conglomerates, quartzites, slates, schists, and gneisses occur in intimate relations to one another, due largely to varying character of material. Nearly every phase of deformation, from that in which granulation is the dominant process to that in which recrystallization is the dominant process, is there represented.

TEMPERATURE.

Low temperature is favorable to granulation; high temperature is favorable to recrystallization. If Barus's experiments upon the solubility of glass[b] be a guide as to the silicates, the temperature of 185° C. is more nearly crucial between the processes than any other. Below 185° C granulation is likely to be prevalent, especially if the deformation be rapid. Above 185° C., if sufficient water be present, recrystallization is probably so rapid that the mechanical strains do not go far before they are largely obliterated by recrystallization.

Temperature increases with depth: the less the depth the greater the tendency to deformation by granulation, and the greater the depth the greater the tendency to recrystallization. But it must be remembered that the mechanical work of deformation itself develops heat, which can escape only by conduction or convection. Therefore, during mountain-making periods, temperatures sufficient for recrystallization may exist much nearer the surface than under quiescent conditions, and consequently recrystallization takes place rapidly at no great depths.

Furthermore, the temperature is raised by intrusive igneous rocks. The heat of the intrusives is conveyed to the adjacent rocks, both by conduction and by convection through water. Hence the presence of igneous rocks is favorable to recrystallization. This has already been dwelt upon. The numerous broad zones of schists and gneisses in which recrystallization is complete about great batholiths, with schistosity everywhere parallel to the sides of the intrusives, have been described. (See pp. 716–717.)

---

[a] Van Hise, C. R., The pre-Cambrian rocks of the Black Hills: Bull. Geol. Soc. America, vol. 1, 1890, pp. 214–230.

[b] Barus, C., Hot water and soft glass in their thermo-dynamic relations: Am. Jour. Sci., 4th ser., vol. 9, 1900, pp. 161–175; vol. 6, 1898, p. 270.

The identical character of the schists surrounding batholiths and those produced in connection with regional mechanical action is explained by the foregoing pages. The necessary conditions for the production of recrystallized schists are movement under sufficient pressure, moderate temperature, and presence of water. These conditions are produced in the two cases in different ways.

PRESSURE AND RAPIDITY OF DEFORMATION.

The less the pressure the more likely is the deformation to be accomplished by granulation. The greater the pressure the more likely is the deformation to be accomplished by recrystallization. The pressure increases with depth, with mechanical action, by igneous intrusions, and possibly from other causes.

To a certain point, the more rapid the deformation the more likely is the adjustment to be by granulation. The limit beyond which this does not apply is reached when the mechanical process develops such an amount of heat that the readjustment is by recrystallization rather than by granulation. The slower the deformation the more likely is the readjustment to be by recrystallization.

WATER CONTENT.

Absence of water is favorable to granulation; presence of water is favorable to recrystallization. If a series be so dense, or is of such origin, that it contains comparatively little water, even if other conditions be favorable, deformation by granulation rather than by recrystallization may occur. Another series, which is in every other respect under similar conditions, but which contains a fair amount of combined water that may be liberated by dehydration to serve as a medium for the process, may be adjusted by recrystallization and form coarse schists. This principle is believed to explain the difference in the character of the deformation of the different formations for many districts. It is a well-known fact that in the same district different rock masses composed of similar minerals deformed in the zone of anamorphism vary greatly in the character of the alteration, some formations yielding by granulation, others by recrystallization. In general the sedimentary rocks contain a considerable percentage of combined water, and therefore when deformed are recrystallized. The same is true of the porous igneous rocks, such as lavas and tuffs. In contrast with these are

the massive igneous rocks, and especially the plutonic rocks, which contain little combined water, and when deformed are apt to be granulated rather than recrystallized. One of the best districts to illustrate the principle is the Original Laurentian area described by Adams.[a] In this district are the anorthosites, the Grenville sedimentary series, and the Basement gneiss of igneous origin. Adams's careful descriptions show that the most fundamental point of difference between the three classes of rocks in their response to deformation is in reference to recrystallization and granulation. The sedimentary rocks of the Grenville series have been completely recrystallized and are typical schists.[b] The igneous gneisses are largely deformed by granulation, but "the granulation has perhaps been effected, in part at least, by recrystallization."[c] The anorthosites have been almost wholly deformed by granulation.[d] Corresponding exactly with these facts are the amounts of contained water. Analyses of three recrystallized Grenville gneisses give an average water content of 1.46 per cent.[e] An analysis of one partly granulated and partly recrystallized gneiss of igneous origin gives 0.70 per cent of water.[f] An analysis of granulated anorthosites gives only 0.51 per cent of water.[g]

The frequent granulation of the massive igneous rocks does not contradict the conclusion (pp. 712–713) that in many cases water as a source of recrystallization may be derived from the plutonic rocks during recrystallization. The very fact that water is given off during this process leaves the plutonic rocks deficient in combined water. When later mass movements take place with only a very small amount of combined water present, granulation is likely to occur, and, as already noted, somewhat in proportion to the amount of the residual water; for, as shown by the illustrations already given, the anorthosites, containing a small amount of water, under mass movement have been granulated to a greater extent than the granites, which contain somewhat greater amounts of combined water.

As examples of recrystallized schists of igneous origin may be men-

[a] Adams, F. D., report on the geology of a portion of the Laurentian area lying to the north of the Island of Montreal: Ann. Rept. Geol. Surv. Canada, vol. 8, 1895, pt. J, p. 184.

[b] Adams, cit., pp. 49–66.

[c] Adams, cit., p. 45.

[d] Adams, cit., p. 106.

[e] Adams, cit., p. 58.

[f] Adams, cit., p. 43.

[g] Adams, cit., p. 130.

tioned the schists and gneisses of the Basement Complex of the Marquette district of Michigan. Two analyses of the Kitchi schists showed, respectively, 2.51 and 2.70 per cent of water above 100° C.[a] A micaceous schist gave off 2.04 per cent of water above 100° C.[b] A Palmer gneiss gave off 2.33 per cent of water above 100° C.[c] Partial analyses of two other micaceous schists from the same locality as the micaceous schist above referred to, which show a cataclastic or granulated structure, unfortunately do not include water determinations.

The foregoing analyses of recrystallized schists from the Archean and Algonkian may be taken as typical of the recrystallized schists of all ages the world over. This is shown to be evident by running through the various analyses of the recrystallized schists in any of the published tables of analyses. Such tables show that the recrystallized schists average more, rather than less, than 1.50 per cent of combined water, and in many cases that they contain more than 2 per cent of water.

In Clarke and Hillebrand's book of analyses,[d] besides those mentioned, are found three other analyses of recrystallized gneisses. The analyses are of typical gneiss, derived from basic granite at Washington, D. C., with a water content (at and above 110° C.) of 1.97 per cent, and two plagioclase gneisses from the Sierra Nevada, with a water content (at and above 110° C.) of 1.71 and 1.47 per cent, respectively. These analyses, with those already quoted, cover all the schists and gneisses cited in Clarke and Hillebrand's book which, from the available descriptions, can be ascertained to be certainly recrystallized. They are here included to show that in this bulletin there is no exception to the rule laid down, viz, that when rocks are deformed in the zone of anamorphism, which contain a sufficient amount of combined water to serve for recrystallization, this process is dominant rather than granulation.

It is to be noted that the water contents of the schists and gneisses mentioned are amounts given off above 100° C., and in most cases above 110° C.; in other words, the water is combined water. This point is of importance as showing that, after the metamorphism of the rocks to schists

[a] Van Hise, C. R., and Bayley, W. S., The Marquette iron-bearing district of Michigan: Mon. U. S. Geol. Survey, vol. 28, 1897, p. 168.

[b] Mon. 28, cit., p. 202, anal. VI.

[c] Mon. 28, cit., p. 217.

[d] Clarke, F. W., and Hillebrand, W. F., Analyses of rocks and analytical methods: Bull. U. S. Geol. Survey, No. 148, 1897, pp. 88, 215.

or gneisses, 1.50 per cent or more of water remained. The percentages of combined water after metamorphism are, of course, no measure of the amount of water, free and combined, contained by the rock before and during the metamorphosing process. It is highly probable that the amount of combined water in the later stages of the process, in the case at least of the sedimentary rocks, is lower than in the earlier stages of the process, consequently water is driven off during the process, thus renewing the water films in the subcapillary spaces, and furnishing a medium for solution and redeposition. (See Chapter III, p. 145.) This is inferred from the analyses of pelites in their various stages of alteration from soils and clays to shales, slates, schists, and gneisses. Sixteen analyses given by Clarke and Hillebrand of soils and clays from Pennsylvania, Florida, and Colorado gave an average loss of water at or above 100° C. of 7.15 per cent. Six analyses of clays and soils from Virginia gave an average loss of water above 110° C. of 8.61 per cent. Forty-four analyses of clays and soils from Massachusetts, South Carolina, Alabama, Missouri, Colorado, Nevada, and California gave an average loss of water upon ignition of 8.10 per cent.[a] Twenty slates and shales from Vermont, Colorado, and California gave an average of 4.42 per cent of water above 100° C. Fourteen slates and shales from Vermont, New York, Kentucky, Georgia, and Alabama gave an average of 4.34 per cent of water above 110° C.[b] The original mudstones from which the shales and slates were produced may be presumed to have contained at least as much water as do soils and clays. The shales and slates are rocks partly metamorphosed during mass-mechanical action, and they certainly lost about one-half of the combined water during the change.

It is well known that shales and slates, when profoundly metamorphosed during mass-mechanical action, produce schists or gneisses. Since most of the schists contain less than 2 per cent of water, this agent was again reduced to one-half or one-third of the amount present when the rocks were in the stage of shales and slates. Therefore the pelites in their original form contain in combination not only a sufficient amount of water to satisfy the requirements as to combined water in the completely metamorphosed schists, but an excess of water, which may be steadily given off

[a] Clarke, F. W., and Hillebrand, W. F., Analyses of rocks and analytical methods: Bull. U. S. Geol. Survey, No. 148, 1897, pp. 287–301.

[b] Clarke and Hillebrand, cit. pp. 277–286.

during the process of metamorphism, and thus constantly furnish a supply of the medium through which recrystallization can take place. The same is certainly true of many other rocks the materials of which have been subject to the processes of alteration in the zone of katamorphism, and which therefore contain hydrous minerals. The most important exceptions are the pure silica and the pure carbonate rocks.

The steadily lessening amount of combined water with increasing metamorphism is illustrative of the facts already explained on pages 178–180, that the deep-seated zone of recrystallization is one of dehydration. In opposition to this, the alterations under conditions of small depth are those of hydration. Many of the rocks metamorphosed under such conditions contain as high or higher percentages of water than the soils and clays the water contents of which have been quoted. If later such hydrated rocks, whether of igneous or of aqueous origin, were subjected to alterations in the zone of anamorphism, recrystallized schists or gneisses would be developed.

In the above no account is taken of the mechanically mingled water. This is undoubtedly always present in important amount in all of the sedimentary and in many of the igneous rocks, and is an additional supply of the agent of transformation. The amount of this mechanical water has already been discussed. (See Chapter III, pp. 124–127.) It varies from a fraction of 1 per cent of the volume in the densest rocks to as high as 50 or more per cent in the more open soils and clays. At the outset of the process of change the mechanically included water is often an abundant source of the agent of metamorphism; but when the rocks become compacted by pressure, or cemented, or both, this water is largely removed. This is likely to take place in large measure in the zone of katamorphism; consequently, when the rocks reach the zone of anamorphism the amount of mechanical water is usually much reduced. It follows that the originally mechanically mingled water, while probably of importance, can not be depended upon as an adequate supply for recrystallization in the zone of anamorphism. Indeed, it is believed that the water freed by dehydration is the most reliable source of water for recrystallization in the zone of anamorphism. (See pp. 662–663.)

The facts presented on the preceding pages give strong support to the idea that presence of water at the beginning of the process of metamorphism

is necessary in order that recrystallization shall readily occur. If the massive original rocks at the beginning of the mass movements do not contain water sufficient for recrystallization to take place, it does not appear that they are likely under normal conditions to gain sufficient water from an outside source. But where intrusives are introduced on an extensive scale, this source of water may make good the deficiency, so that recrystallization may occur. Apparently the amount of water present during recrystallization must be great enough for at least 1 per cent to be left as combined water; for in the deformed igneous rocks containing less than 1 per cent of water granulation is frequent, and the schists and gneisses formed by recrystallization usually contain between 1 and 2 per cent of water. But doubtless in proportion as rocks are deep seated, so that the pressure is great and the temperature high, a decreasing amount of water suffices for recrystallization.

FIG. 19.—Liquid-filled cavities extending across several quartz individuals without change of direction. From Black Hills quartz-schist.

While the minerals of the rocks are steadily dehydrated during the process of recrystallization, not all of the water driven off escapes; a small part of it is caught within the recrystallizing material; and thus are explained the almost infinite number of minute microscopic water inclusions contained in the schists and gneisses. In some instances the water bubbles are arranged along planes of fracture, in which case they appear in the sections as rows of bubbles which frequently extend continuously across many individuals. (See fig. 19.) The arrangement of continuous rows of water bubbles across many minute individuals has been taken as evidence that the minerals are original, whereas it is plain that the correct interpretation is that the bubbles themselves are probably secondary inclusions, as I have fully explained in another place.[a]

Liquid carbon dioxide is frequently associated with the water inclusions. It is believed that in most cases this material is a portion of the carbon dioxide given off by the decomposition of the carbonates during silication. Another and probably larger portion of the carbon dioxide escapes

[a] Van Hise, C. R., The pre-Cambrian rocks of the Black Hills: Bull. Geol. Soc. America, vol. 1, 1890, p. 218.

with the freed water, and is squeezed upward to the belt of cementation. (See pp. 177, 667.)

The foregoing facts seem to show that whether granulation or recrystallization occurs in the zone of anamorphism in a given district in rocks of a certain chemical composition does not depend upon whether the rocks are igneous or aqueous, but, other things being equal, upon whether sufficient water is present, by means of which recrystallization can occur. As this is more frequently the condition in the sedimentary rocks than in the igneous rocks, the sedimentary rocks are more frequently recrystallized than the igneous rocks, though in many instances recrystallization, rather than granulation, has been the process of modification for the igneous rocks.

The experimental work of Adams and Nicolson[a] upon the deformation of marble seems to me to be fully confirmatory of the above conclusions as to the influence of water in determining whether granulation or recrystallization occurs. They deformed marble under conditions of the zone of flowage, both dry and wet, at a temperature of about 300° C. The marble deformed while dry, "if not quite as strong, is at least very nearly as strong as the original rock,"[b] as shown by tests of its crushing strength, whereas the marble deformed at the same temperature in the presence of steam at a pressure of 460 pounds per square inch was "not weaker, but actually somewhat stronger than the original rock."[c] While they conclude that "the presence of water was not observed to exert any influence,"[d] they say: "It is just possible, however, that there may have been a deposition of infinitesimal amounts of calcium carbonate along very minute cracks or fissures, thus contributing to maintain the strength of the rock. No signs of such deposition, however, are visible."[e]

It seems to me that the increased strength of the rock deformed in the presence of steam is positive evidence of the influence of water. When it is remembered that the mineral experimented upon was one which is readily deformed by movement along gliding planes, and therefore one in which for deformation without granulation recrystallization is not necessary, and that the time through which the experiment was

[a] Adams, F. D., and Nicolson, J. T., An experimental investigation into the flow of marble: Philos. Trans. Royal Soc. London, series A, vol. 195, 1901, pp. 363–401.

[b] Adams and Nicolson, cit., p. 379.

[c] Adams and Nicolson, cit., p. 385.

[d] Adams and Nicolson, cit., p. 399.

[e] Adams and Nicolson, cit., p. 385.

continued was but a minute fraction of the time of the action of water under natural conditions, the experiment seems to me to furnish the strongest possible confirmation of the conclusion already expressed as to the importance of the presence of water during the recrystallization of rocks.

ROCK FLOWAGE.

MEANING OF ROCK FLOWAGE.

If the conclusions of the foregoing pages be true, the real meaning of rock flowage, at least as deep as observation extends within the earth, follows as a corollary. It is apparent that the process of rock flowage is very different from the flowage of a liquid or that of a malleable solid, although it involves elements which occur in these processes.

In discussing the subject of rock flowage it will be necessary to repeat the substance of certain things which have already been said. This is necessary in order to bring the different elements which enter into rock flowage into juxtaposition in proper relations to one another. I have previously maintained that deformation at considerable depth is accomplished by rock flowage.[a] However, I made no attempt to explain in detail the nature of the interior movements.

All of the different processes which have been described are involved in rock flowage. That is to say, the mechanical processes of strain within the elastic limit, gliding, granulation, and welding, and the chemical processes of cementation and metasomatism resulting in recrystallization, all enter into the result. In the foregoing pages each of these processes has been separately discussed and their relations have been pointed out. Various combinations of the foregoing mechanical and chemical processes explain rock flowage. Commonly in rock flowage the chemical process of recrystallization is dominant; but this, as has been explained (pp. 690–692), is promoted by the simultaneous mechanical strains. But in many cases of rock flowage the evidences of chemical and mechanical processes are about equally marked, and in some instances of considerable importance mechanical processes have been dominant.

I shall first consider the slates, schists, and gneisses, which are typical examples of rocks that have been deformed by rock flowage, and are also

[a] Van Hise, C. R., Principles of North American pre-Cambrian geology: Sixteenth Ann. Rept. U. S. Geol. Survey, pt. 1, 1896, pp. 593–595, 636–643.

the class of rocks in which the process has taken place on the most extensive scale. It will be remembered that slates, schists, and gneisses are rocks in which many of the mineral particles show parallel orientation and in which the major portion of the mineral particles now show slight or no strain effect. (Pl. XI, *C.*) It is evident that these are rocks which have nearly perfectly accommodated themselves to the deformation through which they have passed. The accommodation, as already explained, is accomplished by continuous solution and deposition, or by continuous recrystallization. While the adjustment during deformation at any moment was nearly as complete as though the rock were a magma, and while it may nowhere show even a microscopic opening, it is evident that the flowage is wholly different from that of a liquid. At no time was the rock a liquid; on the contrary, it was at all times almost wholly a crystallized solid. At no time was more than an almost inappreciable fraction of it in liquid form—that is, dissolved in water—yet at all times it was adjusting itself by means of the small percentage of water contained in the capillary and subcapillary openings, this being the chief agent of deformation working through solution and deposition, or recrystallization. In order that such a continuous process shall be adequate to explain rock flowage, it is necessary only that it shall be sufficiently rapid to keep pace with the deformation. Probably one's first thought is that it is not possible that the process can be sufficiently rapid to account for the phenomena. However, the experiments of Barus on the solution of glass give us a basis upon which we can make a quantitative calculation.

Barus has shown[a] that a temperature of 185° C. is critical so far as the solution of glass by water is concerned. At temperatures lower than this the rate of solution by water is very slow. However, at temperatures of 185° C. and above, solution of the silicates of glass goes on with astonishing rapidity. Barus dissolved, in capillary tubes, a sufficient amount of glass to cause an apparent contraction of volume of the water amounting to 13 per cent of the water present in 42 minutes, and 18 per cent in an hour.

This illustrates the fact that the activity of water at a very moderate temperature is amazing and one need not be surprised at its potency in the alteration of rocks deep below the surface of the earth. Temperatures higher than 185° C. exist at moderate depth, and therefore it is reasonable

[a] Barus, C., The compressibility of liquids: Bull. U. S. Geol. Survey No. 92, 1892, pp. 78–84.

to suppose that a small amount of water may be the medium of rapid and most profound modification of the rocks.

We have already seen (pp. 690–691) that during the process of deformation the material, if not dissolved, may be strained even to the point of granulation by the mechanical processes; also it has been seen that, so far as strain occurs, or the particles are small, the minerals are in a state in which solution is easier than for unstrained or larger mineral particles. But it is probable that the solution of mineral particles and the deposition of the material in an unstrained crystallized condition is considerably slower than the solution of amorphous glass; for, among other reasons, it can not be supposed that the same amount of energy is potentialized in the mineral particles as in the glass. But the further the strain goes before fracture the more energy is potentialized, or if fractures occur smaller particles are produced. Moreover, the contained water is in small capillary or subcapillary spaces, and therefore a given volume is acting upon a much larger surface than in the capillary tubes used by Barus in his experiments. In so far as granulation occurs, the surface of action is still further increased. All these conditions are favorable to solution and redeposition; therefore, the greater the straining and resultant granulation, the more rapid the process of recrystallization; hence, in the deep-seated zone, when water is present in sufficient amount, mechanical disintegration never gets far in advance of solution and redeposition. (See pp. 696–698.)

At temperatures above 185° C., if it be supposed that in the capillary and subcapillary spaces within the rocks the speed of solution of minerals is 0.1 of that of glass, as ascertained by Barus, water would dissolve its own volume of minerals in about five hours. If the deep-seated rocks be supposed to contain 2 per cent of water by volume—that is, less than 1 per cent by weight—the entire mass of rocks might be dissolved in about 250 hours, or little more than ten days, provided deposition went on at the same rate as solution. The percentage of water premised is known to be lower than the amount ordinarily found in the recrystallized schists and gneisses (see pp. 742–743), and the rate suggested seems reasonable; but if the speed of solution and deposition be decreased to 0.1 of that suggested, or to 0.01 of that of the solution of glass, still the entire mass of the rock might be dissolved and redeposited in about 100 days. Make the rate 0.1 of this, or 0.001 of that of the solution of glass, and still recrystal-

lization might be complete in about 1,000 days, or three years. If it be supposed that a mountain-making period occupied 150,000 years—and this is probably less rather than more than the time required for most mountain-making movements—during this period at the slow rate suggested the rocks could be recrystallized 50,000 times by 1 per cent of water, and this number certainly seems adequate to fulfill the requirement that at any given moment the rock shall exhibit but a slight strain effect.

Of course it is not thought probable that any rock has completely recrystallized 50,000 times. Indeed, it is well known that many of the rocks in which recrystallization is complete, in so far as the finer particles are concerned, contain many larger particles which have not been completely recrystallized. Perhaps one of the best instances of this is furnished by the schist-conglomerates. The typical schist-conglomerates contain a schist matrix, embedded in which are numerous large fragments. In many of these the matrix is completely recrystallized, but the fragments, unlike the matrix, show important strains, which not infrequently pass to the point of partial granulation with partial recrystallization. To explain the phenomena exhibited by the perfect schists which have developed during a continuous process of deformation it does not seem necessary to suppose that complete recrystallization is necessary. If the case of a large grain of quartz or feldspar in a recrystallizing rock be taken, we may suppose the process to go on somewhat as follows: Because of the lack of homogeneity of the rock the stresses are irregularly distributed. At the most exposed places upon the mineral particles the conditions are favorable for solution, for the following reasons: The particles are there greatly strained, perhaps to the point of granulation; and, so far as strain exists, or small granules are formed, these conditions are favorable to solution. At the places of great strain the material is therefore taken into solution and transported to the parts of the particles less strained or to other particles. At such places the conditions are favorable to deposition, on account of the relatively large size of the residual original grains as compared with the granules. (See pp. 74–76.) The mineral particles, where least strained, separate from the solution materials like themselves and attach them in orientation with the cores in an unstrained or little strained condition. The process of growth is analogous to that of mineral growth by secondary enlargement. The entire process is similar in several respects to that of

the continuous solution and deposition of calcium carbonate in the chemical laboratory when water is passed through a layer of this material under pressure. Where the pressure is greatest, in the upper part, the grains are taken into solution; at the place of escape, where the pressure is least, the material is deposited from solution and the grains increase in size, or grow.

During the deformation of the rocks this process of solution and deposition of the mineral particles is continuous.

If it be supposed to go on to a stage in which an original particle is one-half or one-third as thick as it was originally, it is not necessary to suppose that the central part of the mineral particle has been recrystallized. This is illustrated by fig. 20. A spherical grain is supposed to have changed to the superimposed spheroidal grain. The common portion C, or a large portion of it, may be an uncrystallized part of the old grain, but the material AA has been dissolved and added to the borders at BB. Corresponding to this explanation, some of the flat quartz grains of the slates and schists of the Black Hills of Dakota show residual cores.[a]

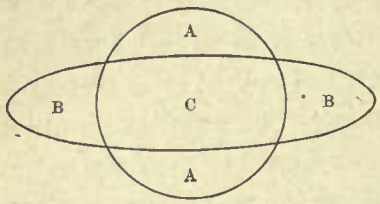


FIG. 20.—The possible relation of old and new grains of recrystallized rocks.

Since in most cases the stresses are unequal in three dimensions, there is a direction of greatest pressure; at right angles to this is a direction of mean pressure; and at right angles to these two, a direction of least pressure. During the process of recrystallization, at any given moment there is maximum shortening in the direction of greatest stress, maximum elongation in the direction of least stress, and shortening or elongation in the direction of mean stress. Consequently the shape of the modified particle may be that which would be produced if a plastic grain were rolled out, the sides being confined in one direction, but with liberty to elongate in another direction in the same plane; or it may be that which would be produced if a roundish cake of dough were flattened between two boards, and consequently elongated in all directions at right angles to the direction of greatest pressure; or, finally, the mean stress may approach so closely to the maximum stress that there is shortening in two directions and elongation in a single one only, in which case a fibrous structure is produced. But from my

[a] Van Hise, C. R., The pre-Cambrian rocks of the Black Hills: Bull. Geol. Soc. America, vol. 1, 1890, p. 224.

study of the slates, schists, and gneisses I am inclined to believe that shortening in one direction and unequal elongation in the direction at right angles to this is the most common case, though my thin sections give illustrations of all the cases. The particles are arranged with their greater, mean, and minor diameters corresponding to least, mean, and greatest pressures. In proportion as the movement involves shearing motion or scission,[a] the mineral particles are rotated from a position in which the direction of greatest elongation is at right angles to the direction of greatest pressure, although at any given time the mineral particles tend to develop with their longer axes at right angles to the maximum pressure.

In some cases the direction of greatest pressure varies within exceedingly short distances. This is illustrated by large rigid particles, such as feldspar, garnet, and other refractory minerals, which act as transmitters of pressure to more than an average extent. Adjacent to the rigid mineral particles the direction of greatest pressure is modified from point to point, thus deviating from the average for the rock. New minerals forming may curve about the rigid granules. This is beautifully illustrated by the flat, curved quartzes adjacent to feldspar in the quartz-porphyry described by Futterer. (Pl. III, *B;* see p. 738.) In this case the flat individuals lack orientation and show undulatory extinction independently of subsequent strain.

The above process of flattening by recrystallization is general; and therefore we conclude that while recrystallization is constantly occurring in the deformation of rocks, at any given time a large number of the mineral particles retain their integrity, and are nuclei which at any moment orient the material being deposited. In many rocks evidence may be seen that this has happened. The old mineral particles, represented by the cores, are partly altered, and in consequence of this may be discriminated from the freshly added material; or the cores show a border of iron oxide or other mineral; or the old and new materials have slightly different compositions, and this may be discovered by a difference in the color, refraction, or extinction, or in some other way. Finally, all of the old mineral particles may be regenerated or recrystallized.

[a] Becker, G. F., Finite homogeneous strain, flow, and rupture of rocks: Bull. Geol. Soc. America, vol. 4, 1893, pp. 24–25.

Therefore a given portion of a definite mineral particle in a slate, schist, or gneiss may not have been recrystallized at all, or, on the other hand, may have recrystallized several or many times. It is believed that ordinarily the recrystallization is far advanced or complete for all parts of a typical schist, although this is far from the case in the semicrystalline schists or imperfectly schistose rocks. Where deformation is mainly accomplished by recrystallization the process may be called recrystallization flowage or chemical flowage.

Of course, during this rearrangement it is not supposed that the identical molecules which are taken from the more severely stressed parts of a grain are necessarily deposited at the places of less stress upon the same grain. Undoubtedly there is great interchange of material between the particles by means of the solutions. It is, however, thought probable that in many cases of deep-seated deformation, where the passage of solutions is difficult and slow, much of the identical material which is taken from a grain at one place is added to it at another place.

When new individuals are produced in any way, as by granulation, or by deposition as new mineral particles, perhaps as different species from any originally in the rock, they are subject to the same laws as the original mineral particles. Many have a tendency to form with dimensional orientation, which usually carries with it similar crystallographic orientation. However, it is only rarely that the orientation of the particles of a given mineral approximates exactness. One mineral—for instance, mica—may be well oriented, whereas such minerals as quartz or calcite may not be oriented.

In proportion as the minerals readily respond to the forces of recrystallization, or are mobile, they do not gain or retain a regular arrangement. After mass movement has ceased the temperature may be high enough and the heat be held long enough for the solutions to completely recrystallize the minerals under mass-static conditions, and therefore orientation may be lost. In proportion as minerals do not readily recrystallize or stubbornly resist the force of recrystallization, the minerals once oriented retain their regularity of arrangement.

The most mobile of the important minerals is calcite. As explained by Adams and Nicolson,[a] the mobility of this mineral is doubtless partly

[a] Adams, F. D., and Nicolson, J. T., An experimental investigation into the flow of marble: Philos. Trans. Royal Soc. London, series A, vol. 195, 1901, pp. 363–401.

due to movement along gliding planes. Quartz is also somewhat mobile. Therefore these minerals in marble and in recrystallized quartzite frequently lack regularity of arrangement. However, in some cases even calcite may show well-developed dimensional and to some extent similar crystallographic orientation. The usual almost complete lack of regular arrangement for calcite is illustrated by most of the marbles from the Laurentian Mountains to Alabama. The complete recrystallization of quartz to a coarse granolitic-textured rock, the individuals wholly lacking orientation, is illustrated by the quartzites of the Wausau district of central Wisconsin.

In the process of recrystallization of rocks it is not supposed that every large mineral particle retains a nucleus for lateral growth; indeed, it is certain that in a rock some large particles of a mineral may retain the modified integrity above described, while other particles of the mineral may be wholly destroyed. It is believed that orientation of the mineral particles in reference to the varying stresses has an influence upon their preservation. If the original particles happen to be in such positions that they would develop as authigenic minerals under the differential stresses, this is thought to be favorable to the preservation of their nuclei and to growth. It is believed that in proportion as the particles vary from such positions the mineral particles are likely to be destroyed. The effect of position with reference to the principal stresses upon the persistence of a given particle is probably great in proportion as the mineral has a tendency to be influenced in its dimensional arrangement and crystallographic orientation by the stress differences which exist during deformation. To illustrate: The position of the axes in reference to the greatest pressure in mica, which shows a marked tendency to parallel arrangement, would be a more important factor in its preservation than in quartz, which only rarely shows regular arrangement.[a]

In the foregoing nonrotational distortion has been assumed. In case the deformation includes a rotational element, during the recrystallization each of the particles would be similarly rotated, as well as flattened or recrystallized, or both; and consequently the direction of the maximum compression, and therefore the most favorable direction of elongation of the mineral particles, would change in reference to them. At any stage

[a] Van Hise, C. R., Principles of North American pre-Cambrian geology: Sixteenth Ann. Rept. U. S. Geol. Survey, pt. 1, 1896, p. 635.

of the process there would be a tendency to retard the growth of the mineral particles which had formed at an earlier stage. Another effect of rotation would be to decrease the regularity of the similar arrangement of the mineral particles as compared with those produced during nonrotational distortion; for at any stage the new mineral particles would form in positions somewhat different from those of the particles formed at an earlier stage. I suspect that in rotation with reference to the forces during development lies the principal cause of imperfect arrangement of the cleavage-making mineral particles of the slates, schists, and gneisses. This point is more fully developed by Leith.[a]

While in the slates, schists, and gneisses many mineral particles are able to maintain themselves, a vastly greater number are probably destroyed by the process of recrystallization. This is certainly true in those very numerous instances in which the average size of the mineral particles of the metamorphosed rocks is much greater than the average size of the particles in the unaltered rocks. It has been pointed out (pp. 674–675) that in many instances hundreds or thousands or even a million or more of particles may be required to produce a single individual. From such cases there are all gradations to those where the particles of the recrystallized rocks are not larger than those of the unaltered rocks, and through these to those in which the particles of the recrystallized rocks are smaller than those of the unaltered rocks. In proportion as the particles of the original rocks are large, an increasing proportion of them, or of parts of many of them, is likely to be preserved in the recrystallized rock. In proportion as the particles of the unaltered rock are small, a decreasing proportion of them is likely to be preserved in the recrystallized rock, although in the latter case the absolute number of mineral particles preserved and enlarged may be as great as or greater than in the former case.

On pages 751–753 the modifications of the forms of the original particles have been considered. Substantially the same principles apply to newly formed mineral particles. With or without a nucleus, a mineral particle begins to grow. Because of the differential stresses the molecules which first segregate to form minerals that have strong crystal habit orient themselves in such positions that their shortest axes are in the direction of maximum pressure, their longest axes are in the direction of minimum pressure,

[a] Leith, C. K., Rock cleavage.

and their mean axes are in the direction of mean pressure. When once the mineral particles have oriented themselves in this way, they continue to grow according to their crystal habits, the most rapid growths being in the direction of greatest pressure. This dimensional arrangement controlling the orientation of mineral particles forming in rocks during conditions of unequal stresses has been formulated by Leith as a result of his detailed studies of rock cleavage.[a] The amount of mass shortening which results in the regular arrangement may be comparatively slight, and yet the differences in the dimensions of the mineral particles be great. For instance, Leith's measurements show that the common ratio between the least and greatest diameters of the mica flakes of mica-schists is, on the average, about 1 : 10.[b] It does not follow, as has been thought by some, that this involves the shortening of the rock mass by 0.9. Indeed, it is perfectly conceivable that the rock mass may be but slightly shortened, perhaps by 0.1, and yet produce mineral particles the shortest dimensions of which are only 0.1 as great as their longest dimensions. During recrystallization of a rock the material of those minerals which have strong crystal habit rapidly attaches itself to the borders of the particles and but slowly to the sides.

The above conclusion seems to be completely confirmed by the constancy of the ratios between the greatest and least diameters for a given mineral. Leith has ascertained that in mica the ratio varies from 100 : 65 in the case of biotite to 100 : 10 in muscovite, with an average of 100 : 20 for biotite and 100 : 14 for muscovite; in hornblende from 100 : 40 to 100 : 25; in feldspar from 100 : 75 to 100 : 50.[c] In the case of each mineral these ratios are practically the same whether the rock be a slate, a fine-grained schist, or a coarse-grained gneiss. The full range of variation in the ratios of a mineral can be found in the same rock in each of the different stages of metamorphism. If the ratios between the least and greatest diameters of the mineral particles were taken as evidence of the amount of shortening of a rock, we should reach a different conclusion for each mineral and the same conclusion for all stages of metamorphism. Such a conclusion is absurd, and the independence of the dimensional ratios of the orienting minerals and the amount of rock shortening is perfectly established. Therefore, so far as new mineral particles are produced with similar

[a] Leith, C. K., Rock cleavage. [b] Leith, C. K., cit. [c] Leith, C. K., cit.

dimensional arrangement, these give no basis to estimate the amount of shortening of the rock.

The case of flattened original fragments is very different. In so far as the resultant material or flattened ovules can be identified with original forms, as, for instance, where conglomerate pebbles and fossils are deformed, these distorted objects give a means of determining the amount of the mass shortening.

In proportion as the conditions are unfavorable for recrystallization—that is, as mineral particles are refractory, as they are coarse grained, as the deformation is rapid, as the depth is small, as the temperature is low, as the water content is small—granulation occurs instead of recrystallization. This is sufficiently evident, without amplification, from the discussion already given. (See pp. 737–748.)

In the imperfect slates, schists, and gneisses, which are widespread rocks, adjustment during deformation is accomplished in part by the process of recrystallization just described, but also in part by the mechanical processes. Of these, granulation with differential movement of the granules and welding of the granules is of first importance. Strain within the elastic limit is of very considerable moment. The deformation of the mineral particles by movement along gliding planes may be of occasional importance, especially in certain classes of rocks, such as marbles.

The cataclastic rocks do not usually show slaty or schistose structures. In these rocks the process of flowage is mainly mechanical. It is chiefly accomplished by the multitudinous fracturing of the solid particles, by differential movements between the minute particles, and by the welding of the differentially moved bodies. With this process as a main one, there is sure to be marked strain within the elastic limit in all the particles, both original and secondary; and thus this is a rather important factor in the process. Finally, gliding is more important than in the case of recrystallization-flowage. But it may perhaps be doubted whether even in the typical granulated rocks the process of flowage is wholly mechanical. In all rocks there is a small amount of water present, and even in the instances of apparently perfect granulation probably solution and deposition, or recrystallization, has taken place to some extent. Where deformation in the zone of anamorphism is mainly accomplished by granulation and differential movement of the particles, the process may be called granulation-flowage, or mechanical flowage.

The illustrations of the perfect schists produced mainly by recrystallization, and of the imperfect schists produced by recrystallization and mechanical strains combined, are so well known that they need not be mentioned. The best illustration known to me of flowage mainly by granulation is afforded by the anorthosites of the Original Laurentian, described by Adams.[a]

So far as the mass deformation is concerned, the rock flowage may be mainly by recrystallization, mainly by granulation and other mechanical processes, or by any combination of them. In all alike there is minute interior adjustment of the particles so as to change the mass form of the rock. It makes no difference, so far as the resultant form is concerned, whether the change is accomplished mainly by the differential movements of the molecules, as in the recrystallized schists, or by the differential movements of granules, as in the cataclastic rocks, or by the two combined.

CONCLUSION.

Rock flow is mainly accomplished through continuous solution and deposition—that is, by recrystallization of the rocks through the agency of the contained water. The recrystallization is largely induced by mechanical strains. Rock flow is partly accomplished by direct mechanical strains. At the beginning of the process of flow, during the process, and at the end of the process, the rocks, with the exception of an inappreciable amount, are crystallized solids. At any moment only an infinitesimal quantity is fluid—that contained in the minute quantity of water present. Yet the solids respond to deformation like plastic bodies, not only not losing crystalline character, but usually acquiring mineral particles of fair magnitude, because the water is ever changing the position of the crystallized material, dissolving a substance here and depositing it there. By this process, combined with the mechanical strains, there is continuous adjustment or adaptation of the mineral particles to their environment, as demanded by the deformation of the rock.

This is rock flow. In this conclusion nothing is said as to the condition of material below that part of the earth which is called the lithosphere, nor as to the meaning of flow in this part of the globe—i. e., the centrosphere.

[a] Adams, F. D., Report on the geology of a portion of the Laurentian area lying to the north of the Island of Montreal: Ann. Rept. Geol. Surv. Canada, new ser., vol. 8, 1895, pt. J, pp. 103–131.

MEANING OF ROCK CLEAVAGE.

The conclusions of the foregoing pages show clearly the meaning of rock cleavage. I have already held that this structure is largely accordant with the cleavage planes of minerals the particles of which have crystallographic orientations; that these particles are mainly authigenic, and therefore that rock cleavage is a capacity to part largely due to the actual cleavage of similarly oriented mineral particles.[a] As the cleavage of mineral particles has long been known to be a molecular structure, it follows that the cleavage of rocks is also largely a molecular structure. I have also explained that the similar crystallographic orientation is frequently, indeed usually, accompanied by an arrangement of the mineral particles with their longer diameters in the same plane as the cleavage, and that this dimensional arrangement is a factor in rock cleavage, although less important in most cases than that of the crystallographic orientation of the mineral particles.[b] Leith has shown that the dimensional arrangement dependent upon mineral habit is the factor which controls the similar crystallographic arrangement.[c]

Where similar dimensional and crystallographic orientation prevails with a number of the important cleavable minerals, and a similar dimensional arrangement without crystallographic orientation prevails with other important minerals, cleavage is perfect. The ruptures take place by taking advantage of the cleavage of the mineral particles or by partings between their longer dimensions, and both these factors give easier rupturing than transverse to the cleavage. Since rock cleavage is fully discussed by Leith in the publication referred to above, no detailed discussion is here made, but it is mentioned in order to put this part of the subject in proper relation to rock flowage.

EFFECT OF ROCK FLOW ON TEXTURES AND STRUCTURES.

As soon as rock flowage, combining mass and molecular movements, is inaugurated, the interior movements begin the destruction of the original textures and structures. With comparatively little flowage the original

[a] Van Hise, C. R., Principles of North American pre-Cambrian geology: Sixteenth Ann. Rept. U. S. Geol. Survey, pt. 1, 1896, pp. 633, 635.

[b] Van Hise, cit., p. 635.

[c] Leith, C. K., Rock cleavage.

textures of some rocks may be wholly destroyed. For instance, such rocks as quartzose sandstones, composed dominantly of a single mineral, which retain their structures for indefinite periods if there be no marked deformation even when buried under a thousand or more meters of other rocks, when deformed in the zone of anamorphism, rapidly lose all clastic textures. In place of the original textures, whether those of sedimentary or those of igneous rocks, in consequence of flowage there appear the peculiar textures of the slaty, schistose, gneissose, and cataclastic rocks.

But while there is a marked tendency to obscure and finally to obliterate textures and structures by flowage, the extent to which this goes is very variable. The larger the texture or structure the less likely it is to be destroyed. Since structures involve larger masses than textures, the former may not be much obscured at a stage when the textures are wholly gone.

During rock flowage, even if there be perfect granulation or recrystallization, or some combination of the two, the resultant rock may preserve the larger textural and structural units of the original rock. This is more likely to be true of granulation than of recrystallization. In rocks composed of a number of minerals, even where granulation is complete, the aggregate of mineral particles resulting from each original mineral particle is commonly preserved as an elongated or flattened disk, the different granules not being mingled to any considerable extent with those of the granules of the associated minerals. For instance, the many granules from a large feldspar grain of anorthosite may constitute an oval area little or not at all mingled with the granules of the adjacent pyroxene. Again, the innumerable granules of a flattened pebble of a conglomerate may be sharply separated from the granules of the adjacent matrix, so that the pebble is easily discriminated.

In proportion as recrystallization takes place the textures are likely to become more rapidly obscured. The solutions transport material for short distances from one mineral particle to another, and thus the products become intermingled. For instance, adjacent feldspar and pyroxene may produce reaction minerals different from each. But even where recrystallization occurs the process must go to an extreme before the flattened pebbles of a coarse conglomerate are wholly lost. Even when the matrix is a coarse schist or gneiss the flattened disks of the pebbles are often

recognizable in a section transverse to the greatest elongation. But where the metamorphism is extreme the pebbles may be so greatly flattened as to allow the solutions to mingle the materials of the pebbles and matrix, and thus the pebbles be wholly lost.

But even with most extreme metamorphism by recrystallization the larger structures are usually preserved, although the process may occasionally go so far as to make the strata or even the beds indistinguishable; but it rarely, if ever, goes so far as to obliterate formations. Excluding igneous action, interstratified sedimentary formations of, for instance, sand, mud, and limestone, have rarely been so profoundly metamorphosed as to make them indistinguishable. The composition of a formation is the most prominent feature by means of which the original nature of a rock can be recognized. Where there are metamorphic formations having the approximate chemical compositions of sands, muds, and limestones, we may be sure that such formations are sedimentary. Rock flowage may wholly obliterate the clastic textures, and even the bedded structures; but there is not sufficient kneading and intermingling of the materials to obliterate major structures. That this should be so is precisely what we would expect when we understand that rock flowage is accomplished not by recrystallization from fusion, but by recrystallization and by granulation of the individual mineral particles, the rocks remaining solids throughout the transformations.

ROCK FLOWAGE AND MASHING.

In another place I have proposed the term "mashing" to describe the process of mass deformation in the zone of rock flow.[a] It has been seen that rock flow involves the universal participation of the mineral particles. The preceding study shows that this participation may be by recrystallization or by granulation, or by the two combined; but in the field, where microscopical work is not usual, it is difficult or impracticable in many cases to discriminate between these two processes. Therefore it is very convenient to have a word which will cover deformation by rock flowage without reference to the detailed effects upon the mineral particles, and for this purpose it has seemed to me that the word "*mashing*" expresses

[a] Van Hise, C. R., Principles of North American pre-Cambrian Geology: Sixteenth Ann. Rept. U. S. Geol. Survey, pt. 1, 1896, pp. 694–696.

better than any other the macroscopical point of view of the zone of flow. Without further exposition, which would involve repetition, I propose the term "mashing" to cover mass deformations of all kinds in the zone of rock flow.

The term "mashing," thus used, includes much of the process which has usually been described under the terms "dynamic metamorphism" and "shearing." The term "dynamic metamorphism" is objectionable for many reasons; it will here simply be said that fracturing in the belt of cementation is equally dynamic metamorphism; but the effects in the two zones of flowage and fracture contrast so sharply that they should not be confused. The term "shearing" has been used in a very loose and most objectionable manner. Most authors who have used it mean differential movement along a certain set of parallel planes, but apparently most geologists who have thus used the term do not recognize that shearing parallel to one plane is invariably accompanied by shearing in other planes. Nor is it generally understood that when rocks are compressed by shortening without rotation this is possible only by shearing along all sets of diagonal intersecting planes. In short, in all cases which have been described as shearing and as shortening there is maximum shearing along two sets of intersecting planes and maximum shortening and elongation in the two directions half way between the two sets of shearing planes. Further, as the term "shearing" is ordinarily used, it seems to be assumed that there results a structure parallel to the one set of shearing planes, whereas this may or may not be true.[a] Therefore, to avoid errors implied by the terms "dynamic metamorphism" and "shearing," the term "mashing" is introduced, and from this term the implications which attach to the others have been excluded.

In this connection it should be noted that mashed rocks and their constituent portions, such as pebbles and minerals, are frequently spoken of as stretched. For the most part, this term can not be applied to rocks in the same manner that it is applied to india rubber or steel. In general, the facts upon which the statements as to stretching are made are simply that the rocks show evidence of being longer in a certain direction than they were originally. However, it does not follow from this that the rocks

[a] Hoskins, L. M., Flow and fracture of rocks as related to structure; appendix to Van Hise, C. R., Principles of North American pre-Cambrian geology: Sixteenth Ann. Rept. U. S. Geol. Survey, pt. 1, 1896, pp. 860–866.

have been stretched. Most rocks and minerals when stretched quickly pass their elastic limit, rupture takes place, and the dissevered parts are drawn away from each other, often without deformation of the separated masses. The elongations of rocks and portions of rocks are in most cases explained not by pulling or stretching, but by compression or mashing in a direction transverse to that of the elongation, but this process does produce tensile stresses, which often dissever the mineral particles. But the use of the word "stretching" in reference to such rocks implies that tensile stress is the dominant force. The term "stretching" should be dropped, except in those instances where it is shown that tensile stress has been the primary cause of deformation.

CHANGES IN CHEMICAL COMPOSITION.

If injection be excluded, changes in the chemical composition of the rocks during metamorphism in the zone of anamorphism are not nearly so great as they are in the zone of katamorphism. It has been explained that in the latter zone, both in the belt of weathering (see Chapter VI, pp. 507–518) and in the belt of cementation (see Chapter VII, pp. 655–656), the chemical composition of the rocks may be very greatly modified. Indeed, the changes of chemical composition are most profound in the belt of weathering, and are very important in the belt of cementation. The great changes in these belts are due to rapid and continuous circulation of water, by means of which large quantities of material are transported from one place to another. It has been explained that in the zone of anamorphism the amount of water present is very small and its circulation exceedingly slow. It follows that the water is not capable of transporting large quantities of material considerable distances and thus making great changes in the chemical composition of the rocks through extensive areas. In this we have the explanation of the relative constancy of the chemical composition of the equivalent unmetamorphosed and metamorphosed rocks of the zone of anamorphism. While chemical changes do not greatly modify the average composition of masses of rocks, it has been explained (pp. 682–685) that there is important migration of material for short distances, and therefore profound interior readjustment of the elements in different mineral combinations.

Excluding injection, the chief chemical changes applying to the rock masses as wholes are those of dehydration and decarbonation. Deoxidation

also occurs. The water and carbon dioxide eliminated from the chemical combinations are largely squeezed out of the zone of anamorphism (see pp. 665–667), but a subordinate amount may remain as inclusions in the minerals developed. (See pp. 667–678.) The absolute losses of these compounds is considerable. The loss of hydrogen, oxygen, and carbon dioxide increases somewhat the percentage of the other elements, but does not affect their relative proportions. Excluding hydrogen, the relative proportions of the bases are substantially the same before and after alteration. The replacement of carbon dioxide by silica reduces the amount of carbonates, increases the quantity of silicates, and lessens the amount of free quartz; but the absolute quantity of silica remains the same. In discriminating the metamorphosed sedimentary from the metamorphosed igneous rocks, it will be shown on pages 914–915 that in many cases the proportions of the important chemical elements furnish the best criteria for separating the two classes of rocks.

While in the absence of intrusives there is small change in chemical composition of the rocks in the zone of anamorphism, there may be great changes in the chemical composition where injection is an important factor in the metamorphism (see pp. 711–720), for by injection material different in chemical composition from the injected rock may be intruded in various amounts and in various degrees of division for extensive areas. (See pp. 708–711.) The changes in chemical composition of the rocks where injection is important may be as great as or greater than in the belt of cementation.

The difference in the amount of chemical changes in the rocks in the belt of cementation and in the zone of anamorphism under ordinary conditions, and the difference in the amount of change in the latter zone where injection is absent and where it is present, explain some of the differences of opinion which are prevalent among geologists. One geologist says that metamorphism does not alter the composition of the rocks; another says that metamorphism greatly alters the chemical compositions of the rocks. Each has a part of the truth. Probably the facts with which each is familiar verify his point of view, but each makes a mistake in supposing that a narrow set of facts covers the entire field. The truth of the matter is, as explained, that there are profound changes in the chemical composition of the rocks in the belt of weathering, great changes in the belt of cementation, and considerable changes where intrusion is important in the zone

of anamorphism. But the alterations in the zone of anamorphism where intrusives are absent do not result in great changes in the chemical composition.

RELATIONS OF ZONE OF ANAMORPHISM TO ZONE OF KATAMORPHISM.

It has already been intimated that the zones of anamorphism and katamorphism are not sharply separated, and that there is a gradational belt between them. This gradational belt follows of necessity from the varying character of the rocks and from the varying forces and agents at work. One rock is of a chemical and mineral composition which readily alters; another is of a composition which alters with difficulty. One rock is weak; another is strong. At one place the conditions are mass-static, or those of quiescence; at another they are mass-dynamic, or those of movement. In one place igneous rocks may be absent; in another, abundant. In one place the temperature at a given depth may be low; at another, relatively high. The amount of water has the widest range. Hence it is inevitable that there should be no sharp bounding plane between the zones of katamorphism and anamorphism.

The weak or readily alterable rock may be changed by the reactions of the zone of anamorphism, while a stronger and more refractory rock below may be altered by the reactions of the zone of katamorphism. Moreover, the same rock in the same position, because of varying conditions, may be altered by the reactions of the zone of katamorphism and at a different time by those of the zone of anamorphism. It follows that there is a belt of considerable width in which we may have at one time, under one set of conditions, the reactions of hydration, carbonation, and oxidation, with expansion of volume; and at another time, under another set of conditions, the reactions of dehydration, silication, and deoxidation, with diminution of volume. Neither oxidation nor deoxidation is prominent in the intermediate belt.

We therefore have in an intermediate belt the metamorphic results of the belt of cementation, or those of the zone of anamorphism, or various combinations of the two. In one place we may find the metamorphic effects of the belt of cementation superimposed upon those of the zone of anamorphism; in another we may find those of the zone of anamorphism superimposed upon those of the belt of cementation.

In order to understand more fully the phenomena in this transition

belt, we may consider the metamorphism of an imaginary rock of homogeneous character, composed of a single mineral which extends from the surface to an indefinite depth. Near the surface the rock is broken into blocks by faults and joints. There is no marked deformation of the individual particles, except in thin layers along the fractures. The textures of the rocks are for the most part preserved. Deeper down the fractures are closer together, and at sufficient depth the layers may be no thicker than leaves. Still deeper down every particle takes part in the deformation. This is the belt in which granulation is prominent, although with it there may be some recrystallization. Still deeper down recrystallization becomes important, and finally dominant. In the intermediate belt fracture and flowage do not exclude each other; both occur to varying extent in different positions at the same time.

The transition above described for a single formation composed of a single mineral takes place at different depths for different formations and for different minerals of the same formation, and hence it is that in heterogeneous formations all the phenomena discussed under both the zone of katamorphism and the zone of anamorphism may occur together.

At a given depth the stronger or less readily recrystallized rocks may be largely deformed by fracture, and the weaker or more readily recrystallized rocks be largely deformed by flowage. The result is that original textures and structures may be more or less preserved in the former, while in the adjacent layers original textures and structures may be entirely destroyed and the rocks become slates or schists. It very often happens that the alternating beds which show original textures and structures and those in which they are obliterated are not more than a few inches thick.

In the intermediate belt many of the beds are deformed by combined mass fractures and fractures of the individual mineral particles, so that in the same rock in which joints, faults, fissility, etc., and the alterations attending these phenomena occur, there are also found, between the major fractures, all grades of deformation by interior movement, from the earliest stages of peripheral granulation of the grains to complete granulation or recrystallization, extending throughout the mineral particles. Thus we have all combinations of macroscopic and microscopic fractures and recrystallization.

In some places the intermediate belt is broad; in other places it is narrow. The phenomena of the belt may be seen in aqueous and igneous rocks alike. Many illustrations of each might be given.

As typical cases of sedimentary formations altered in the intermediate belt may be mentioned the Wewe and Siamo slates of the Lower Marquette series, the Goodrich quartzite, and the eastern half of the Michigamme formation of the Upper Marquette series, all in the Marquette district of Michigan.[a] Within these formations almost every one of the multifarious reactions described, both within the zone of katamorphism and within the zone of anamorphism, are beautifully illustrated. Indeed, it was a study of these formations which first suggested to me the idea of a combination of the phenomena of different alterations near the surface and at depth, and the very great difference in the alterations which often occur at the same depth under mass-static conditions and under mass-dynamic conditions.

In Calaveras Creek, a short distance below Calaveras Valley, south of San Francisco, in the Coast Ranges of California, may be seen all stages of transition between a brecciated igneous rock and a schist. The first was deformed under the conditions of spaced fractures. The second was deformed by granulation and recrystallization. In passing from the breccia to the schist one first finds about the blocks of igneous rock which have their characteristic textures mere films of schist. Farther toward the schist is found an intermediate stage in which unmashed blocks lie in a schistose background or matrix. But a short distance from this place is the completely altered schist, in which no unmashed fragments remain. Every stage of the transition is seen. The alterations within the blocks are those of the zone of katamorphism. (See pp. 160–167, 187–191, 599–602.) Within the films and layers of schists constituting the matrix in which the blocks rest and in the main mass of schist the alterations are those of the zone of anamorphism. (See pp. 167–170, 187–191, 657–659.)

These cases of the combination of the phenomena of metamorphism of the zone of katamorphism and those of the zone of anamorphism are but typical of almost innumerable illustrations. The phenomena in any one case are very complex and intricate. Detailed consideration of any single instance would require much space, and it is yet too early to attempt to classify the different cases of various combinations of the alterations of the zones of anamorphism and katamorphism.

---

[a] Van Hise, C. R., and Bayley, W. S., The Marquette iron-bearing district of Michigan: Mon. U. S. Geol. Survey, vol. 28, 1897, pp. 1–608.

COMPARATIVE ENERGY REQUIRED FOR DEFORMATION IN ZONES OF KATAMORPHISM AND ANAMORPHISM.

The question of the amount of energy required to produce deformation in the zone of katamorphism, in the intermediate zone, and in the deep-seated zone of anamorphism is of great importance.

The energy for rock deformation may be divided into two parts—energy for mechanical work and energy for chemical work. The mechanical work is of three kinds—the subdivision of the rocks, the transfer of the material in order to produce a changed form, and the friction between the parts of the subdivided rocks during the transfer.

The most useful comparison as to the amount of energy spent in the different zones is upon the basis of average mass deformation. By average mass deformations I mean the strains necessary to change the shape of unit masses of rock in a nearly similar way, so that the exterior forms are practically the same. To illustrate: A cubic foot of rock may be supposed to be divided into ten horizontal slices and sheared parallel to these slices, so as to produce, ignoring the minor corners, a roughly rhomboidal mass (fig. 21). If instead of ten there were a hundred slices, the approximation to a rhomboidal mass would be closer; if a thousand, closer still; and so on, until the slices became of infinitesimal thickness, when the mass would be rhomboidal. In all of these strains the mass deformation averages about the same.

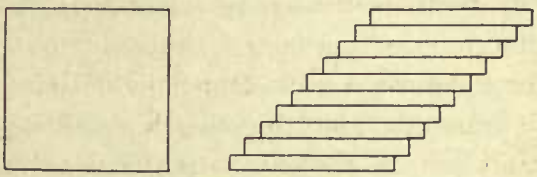


FIG. 21.—Illustrating mass deformation of a rock.

It is perfectly clear in the case of this hypothetical deformation that the amount of work in rupturing is directly as the number of slices. The average mass deformation is substantially the same, and the energy required for change of form—in other words, for transfer of material—is nearly constant. The total amount of differential movement or shear is practically the same in all cases, and therefore the friction is nearly constant. Hence, in the case of the illustration, the energy for the deformation is almost directly as the number of slices. But in the case of the crust of the earth, supposing the fracturing to become closer as depth increases, the energy

required for a given mass deformation would increase with depth for two reasons: (1) More energy is required for the finer subdivision; and (2) the load increases with depth, and therefore the energy required to overcome friction also increases with depth. The energy required for the similar transfers of material remains practically the same at all depths.

It has already been seen that near the surface the dominant deformations are relatively wide-spaced faults and joints; that with increase of depth the spacing between the faults and joints decreases until the fracturing is that of fissility and finally of granulation.

It is therefore clear that the amount of energy required for fractures a considerable distance apart, such as prevail where faults or joints, or both, are the dominant deformations, is much less than where the fractures are close together—as, for instance, in fissility. Furthermore, it is clear that the amount of energy required for the slicing of fissility is much less than that required for granulation of the individual particles, for in the latter case a mass equivalent to a fissile leaf must be broken into a multitude of particles. Probably the ratio between the energy required for breaking a rock into fault or joint blocks near the surface and that required for producing fissile leaves deeper down is not greater than the ratio between the energy required to produce fissility and that required to produce granulation throughout at a still greater depth. No general ratio between the amount of energy spent in deformation by faults and joints and deformation by granulation can be given, but it is certain that the amount of energy used in extreme cases of the latter may be indefinitely greater than that required for the former.

Since it is certain that in passing from the surface to considerable depth there is a passage from deformation by faulting or jointing, or both, to deformation by granulation, it is certain that to a depth of many hundred meters there is a steady and very rapid increase in the amount of energy required for a given mass deformation.

At sufficient depth, as has been seen, granulation is more and more replaced by recrystallization, and finally this process is dominant. It would be very interesting to know exactly the relative amounts of energy required for the two processes of granulation and recrystallization.

As already noted, the energy required for granulation is wholly mechanical, and includes three factors—(1) that required for the subdivision

of the rocks, (2) that required for transfer of material, and (3) that required to overcome friction.

The energy factors in recrystallization are four in number:

(1) Energy is continuously used in straining minerals during deformation, but it is impossible to determine the amount of straining which takes place, for evidence of the strain is continuously obliterated by solution and deposition. If the mechanical stresses did not continuously produce a state of strain, and thus disturb the equilibrium, it is probable that the rate of the process of solution and deposition would be very slow. It is this constant mechanical work in producing strain that keeps the process of recrystallization going.

(2) Energy is required for the transfers of materials by solution.

(3) Energy is required to overcome the viscosity of the solutions, or, stated in a different way, energy is required to overcome the friction of the molecules against the water during their movements.

(4) As a result of solution and deposition in the lower zone, the minerals produced are, on the average, more compact than before the process. In so far as a more compact condition results energy is liberated. On the other hand, the dominant chemical reactions of deoxidation, silication involving decarbonation, and dehydration all demand a large amount of energy. The energy thus consumed is probably greater than that liberated by condensation. It is therefore thought to be probable that the process of solution and deposition consumes energy. In the rare cases in which the minerals are equally compact before and after the process, and no chemical change takes place, as in the recrystallization of a limestone, the energy of solution and that of deposition balance.

We may now compare the energy demanded for each of the different factors in the two processes of granulation and recrystallization. The three factors entering into granulation are paralleled by the first three of the four factors mentioned below entering into recrystallization. (1) It appears probable that the energy required to produce granulation is greater than that required to produce a state of strain during recrystallization. (2) The energy required for the actual transfer of the material by granulation and by solution may be supposed to be the same. (3) The energy required to overcome friction during granulation is certainly vastly greater than the energy required to overcome the friction of the molecules against the water

during the transfer of the material. (4) As a result of the solution and redeposition, energy is consumed.

Therefore the energy required to accomplish granulation, on account of the greater work of subdivision and the much greater work necessary to overcome friction, is almost certainly greater than the energy required for recrystallization.

If one premises that when the conditions are such that either granulation or recrystallization might occur the process takes place which requires the less expenditure of energy, this furnishes additional support to the above conclusion; for wherever the conditions are such that recrystallization can replace granulation, this occurs.

In the artificial deformation of dry marble in the experiments performed by Adams and Nicolson,[a] the deformation was accomplished by gliding and granulation. When the deformation was made in the presence of steam, the adjustment was, to a small extent, by recrystallization.[b] (See pp. 747–748.) If the conditions could be so varied as to accomplish the deformation by recrystallization mainly, it would be interesting and important to compare the amount of work done upon the mass during deformation under these different conditions; for if this could be done it would be possible, at least in this case, to make an estimate of the relative energy demanded by deformation through granulation and through recrystallization. Doubtless this would be a difficult task. It would be necessary to separate the total work done in the machine into the parts which were required for the deformation of the rock mass and that required for the deformation of the surrounding iron, and in one case also to estimate the energy furnished by the water. If it were possible to make the determination, I anticipate from the analysis of the previous pages that the energy required for deformation through recrystallization would be less than that required for deformation through granulation.

The question naturally arises, If less energy is required for recrystallization than for granulation, why did the latter process occur extensively during mountain making in various regions? The answer is plain. Recrystallization can not take place except where the proper conditions of temperature and moisture are present. If the nucleus of the earth be shrinking, the lithosphere must be reduced in size to accommodate itself to this nucleus.

---

[a] Adams, F. D., and Nicolson, J. T., An experimental investigation into the flow of marble: Philos. Trans. Royal. Soc. London, ser. A, vol. 195, 1901, pp. 376–382.

[b] Adams and Nicolson, cit., pp. 382–385.

This implies crustal deformation which extends to the surface, and therefore to places where the conditions are not such that recrystallization can take place.

From the foregoing considerations, I believe that the amount of work done, in order to produce the same mass deformation of the rocks, increases to a certain depth and then decreases until the belt of the perfect schists is reached. How far down this holds I am unable to conjecture, but believe it is probable that it does so at least as deep as the zone in which the schists formed by recrystallization develop, and that it may continue much farther.

The deformation of this deep-seated zone may or may not require the elevation of the superincumbent mass. Where the superincumbent mass is not elevated it is concluded that the energy required for deformation by recrystallization per unit mass is probably less than that required for deformation by granulation, and may be less than that required to produce the spaced fractures which occur near the surface. Where the deformation is of the kind which requires the elevation of the superincumbent material, energy is needed, not only to do interior work of deformation, but to elevate this material. Where these conditions obtain it may be that the amount of energy required to produce the deformation steadily increases with depth on account of the energy required for lifting the load in addition to that required for the interior deformation.

So far as I know, the region in America which best illustrates all the phenomena from deformation by widely spaced thrust faults and by joints to the interior deformation of recrystallization is the Southern Appalachians. In the Great Valley the Paleozoic rocks are little deformed except by thrust faults and joint folds. Eastward, deeper into the mountains, the faults and joints become closer together, and are finally replaced by numerous closely distributed fractures. At the same time the rocks show more and more evidence of metamorphism, first by granulation, and second by recrystallization. In the cores of the mountains are rocks which have largely or completely recrystallized, being slates, schists, and gneisses, with well-developed cleavage. In the valley we find the alterations to affect but a small part of the mass of the rocks now exposed. The deeper we go into the mountains the larger is the proportion of the material which was affected by the alterations, and in the schists in the core the entire mass was modified, both in a mechanical and in a chemical way. In this passage it becomes clear that for a certain distance the amount of energy required for deformation per unit mass increased, but this tendency may have been

reversed in the deepest seated zone. However, since this latter zone is a region of uplift, and the work required for the raising of the superincumbent strata must be added to that required for the interior deformation of the rocks which we now see, no positive statement can be made as to whether the total energy increased or decreased per unit mass in the deformation of the deeper seated rocks.

The conclusions of the previous pages concerning the energy required for a given mass deformation at different depths gives a possible explanation of the concentration of superficial deformation found in mountain ranges. If the energy of deformation be less at the depth at which the slates, schists, and gneisses develop than in more superficial belts, it is possible that the more rigid outer shell of the earth may shear over the nucleus in the zone at which the schists develop, the deformation being widely distributed. Such shearing for a considerable area may require less expenditure of energy than would be demanded for the similar deformation of the rocks above; but during the earth movements, as a result of cooling and other changes, the superficial material must certainly be deformed and shortened,[a] and at such places deformation is concentrated and mountain ranges are formed. This subject is, however, better discussed in Chapter X, under the heading "Relations of rock flowage to mountain making."

CONCLUSION.

The energy required to produce a given mass deformation increases downward to the bottom of the zone where deformation is chiefly by fracture. In deformation by recrystallization the energy required to produce a given mass deformation is probably less and may be much less than that in the lower part of the zone of fracture. By observation we see that recrystallization does take place wherever that process can occur. We have shown that the amount of water present in the rocks wherever recrystallization takes place is adequate to accomplish the process. In the fact that less energy is required for recrystallization than for granulation lies the most fundamental answer to the question why recrystallization rather than deformation by fracture takes place wherever the conditions are such that the former process can occur. Nature is a great economist, and expends the minimum amount of energy to accomplish her work.

[a] Van Hise, C. R., Estimates and causes of crustal shortening: Jour. Geol., vol. 6, 1898, pp. 41–64.

CHAPTER IX.

ROCKS.

In the preceding chapters I have considered the forces and agents of metamorphism, the divisions of the lithosphere into zones of metamorphism upon a physical and chemical basis, the alterations of each of the important rock-making minerals in reference to the zones in which they occur, and the general nature of the alterations of rocks in the belt of weathering, the belt of cementation, and the zone of anamorphism. It now remains to consider the metamorphism of individual rocks, but for a number of reasons it is impossible to do this part of the work satisfactorily at the present time.

In papers upon metamorphism there has in general been no attempt whatever to consider the subject from the points of view set forth in the previous chapters. The usual practice has been to describe the metamorphism of a given region or district and give various conjectures as to the causes of the alterations, often with little or no reference to the different belts and zones of metamorphism. To some extent the belt of weathering has been recognized as having distinctive reactions. The general neglect of the principles of physics and chemistry in the consideration of metamorphism renders it impossible in most cases to interpret the descriptions of the phenomena from the points of view discussed in this volume. If the principles of metamorphism set forth in the foregoing chapters are well founded they should be considered in the study of individual instances. If these principles be recognized it will be comparatively easy to describe a given case of metamorphism in reference to them. When this work is done for a sufficient number of districts it will then be possible to write a satisfactory chapter upon the metamorphism of individual rocks.

A second insuperable difficulty preventing a systematic treatment of the metamorphic igneous rocks is the status of the classification of these rocks. At the present time there is not only no consensus of opinion concerning

a classification of such rocks, but there is not even an approximation to a consensus of opinion as to the principles upon which a classification should be based. Until the original igneous rocks are satisfactorily classified it is quite impossible satisfactorily to consider their metamorphosed equivalents. The situation in reference to the original sedimentary rocks is somewhat more fortunate. There is rather general agreement as to the principles upon which the classification of the sedimentary rocks is to be based, and upon the main classes, orders, and families of rocks which shall be recognized. I shall therefore attempt to consider the metamorphism of each of the main divisions of the altered sedimentary rocks, but shall not make a similar attempt for the igneous rocks.

USE OF SOME GENERAL TERMS APPLIED TO METAMORPHIC ROCKS.

The more important of the terms generally applied to metamorphic rocks are the prefixes *meta* and *apo*, and the general names "slate," "schist," and "gneiss."

META.

The prefix *meta* is used in this treatise in a general way to indicate any kind of alteration of any kind of rock. This usage of the prefix corresponds with the definition of the term "metamorphism" as given in Chapter I, page 32, where metamorphism is defined as meaning all kinds of alterations of all rocks by all forces, agents, and processes. In the sense proposed we may say meta-sandstone, meta-shale, meta-arkose, meta-dolerite, etc. We may even apply the prefix meta to a rock already metamorphosed which has undergone a second set of changes, as, for instance, meta-graywacke and meta-quartzite. Thus used it means that a rock which had first been transformed to a graywacke or quartzite, respectively, was afterwards again metamorphosed.

APO.

The prefix *apo* is here used as a qualifier to indicate metasomatic changes in rocks in which the original textures and structures are largely preserved. This usage of *apo* accords with the underlying idea of the term as proposed by Doctor Bascom.[a] She proposed to call a rhyolite which has

[a] Bascom, Florence, Aporhyolite of South Mountain, Pennsylvania: Bull. Geol. Soc. America, vol. 8, 1897, pp. 393–396.

all the textures of glass, but which has been completely devitrified, aporhyolite. In her original definition she restricted the term to this single alteration, but later she enlarged the meaning[a] so as to include not only devitrified glasses but alterations of all rock in which the original textures and structures are preserved.

The prefix *apo* thus used discriminates rocks which have been metamorphosed under mass-static conditions and retain their original textures and structures from those which have been metamorphosed under mass-dynamic conditions, so as to destroy or partly destroy the original textures and structures and to produce slaty, schistose, or gneissic structures. A rock to which *apo* is prefixed may differ greatly from the original rock in both chemical and mineral composition.

The term *epi* was proposed by Gümbel[b] as a prefix for rocks which have undergone a change in mineral composition, and which by this change have come to have the same mineral composition as another rock. Thus a diabase the pyroxene of which has changed to amphibole, and which, therefore, has the mineralogical composition of diorite, he calls an epidiorite. The term diabase itself was originally applied to an altered dolerite, which has as an important constituent secondary chlorite. Applying the method which is proposed to be here followed, the rock which Gümbel calls epidiorite would be called apodolerite. This name is much more satisfactory than that of Gümbel, since it gives the original nature of the rock, and tells that a part or all of its minerals have altered, but that it retains its original textures and structures. Therefore the name apodolerite gives a better understanding of the history and relations of the rock than does the name epidiorite.

In a manner similar to the above *apo* may be prefixed to any rock altered under mass-static conditions, when it is desired to call attention to the rock from which it was derived. Thus quartzite is an aposandstone; graywacke is an apogrit, etc. The term *apo* thus used supplements the terms schist and gneiss, its usage being structural in a negative sense—that is, applied to metamorphic rocks in which the textures and structures have not changed.

---

[a] Bascom, Florence, Volcanics of Neponset Valley, Massachusetts: Bull. Geol. Soc. America, vol. 11, 1900, pp. 121–122.

[b] Gümbel, K. Wilhelm von, Geologie von Bayern, Kassel, 1888, vol. 1, p. 125.

SLATE AND SCHIST.

Slate and schist are here used as general terms which are applicable to all rocks having a well-defined cleavage in which the cleaved plates are essentially like one another. I have explained in another connection that cleavage in rocks is due to the arrangement of the mineral particles with their longer diameters or readiest cleavage, or both, in a common direction, and that this arrangement is caused, first and of most importance, by parallel development of new minerals; second, by the flattening and parallel rotation of old and new mineral particles; and third, and of least importance, by the rotation into approximately parallel positions of random original particles.[a] Subsequently Leith has shown that parallel slicing may also be a subordinate factor. In a slate or schist the cleavage may or may not be parallel to an original structure such as bedding, but usually it intersects the original structures. Cleavage is fully discussed by Leith.[b] His work shows that cleavage ultimately rests upon a parallel dimensional arrangement of the mineral particles, but for some minerals this dimensional arrangement carries with it mineral cleavage, and the cleavage of these minerals is usually the controlling factor in rock cleavage. Moreover, he argues that the dimensional arrangement is mainly caused by recrystallization. His work while advancing in an important way the theory of cleavage also confirms my own view in showing that rock cleavage is mainly due to the actual cleavage of mineral particles produced by recrystallization, and subordinately due to the easy separation between mineral particles in the direction of their greater dimensions.

The production of slate and schist requires recrystallization during mass-dynamic action. Previous textures and structures are partly or wholly obliterated. In these particulars slate and schist contrast with those rocks to which the term *apo* may be prefixed.

SLATE.

Slate is defined to include those cleavable rocks the cleavage pieces of which are like one another and the mineral particles of which are for the most part so small as to be invisible to the naked eye. The typical example is furnished by the roofing slates, which, so far as the eye can see, are gray

[a] Van Hise, C. R., Principles of North American pre-Cambrian geology: Sixteenth Ann. Rept. U. S. Geol. Survey, pt. 1, 1896, p. 635.

[b] Leith, C. K., Rock cleavage.

or black, homogeneous, aphanitic rocks, which may readily be parted into thin plates which are indistinguishable from one another. The microscope shows that the cleavage of these rocks is due to the causes above given.

The foregoing definition of slate is purely structural. It involves no implication as to the minerals which compose the slate. It says nothing as to whether the rock from which a slate is derived is sedimentary or igneous. If it be desired to ignore the origin of a slate and to indicate its mineral composition, this may be accomplished by prefixing mineralogical qualifiers. For instance, if a slate be composed of mica and quartz as the chief constituents, it is a mica-quartz-slate. If it be desired to emphasize the slaty structure, and at the same time to indicate the original rock from which the slate is derived, the name of this rock may be prefixed. For instance, if a slate be derived from mud, it may be called a pelitic slate or pelite-slate; if a slate be derived from dolerite, it is a doleritic slate or dolerite-slate, etc. If it be desired to emphasize the original rock from which the slate is derived, and only secondarily to indicate that the rock has a slaty structure, this may be done by placing the word slate in the first position; as, for instance, slaty pelite or slate-pelite, and slaty dolerite or slate-dolerite. Finally, mineralogical qualifiers may be prefixed to the above compound names, as mica-quartz-pelite-slate or mica-quartz-slate-pelite.

SCHIST.

Schist is defined to include those cleavable rocks the cleavage pieces of which are like one another and the mineral particles of which are for the most part so large as to be visible to the naked eye. The thin cleavage plates of a schist which are like one another are called folia, and the rock is spoken of as foliated. The most important of the cleavage-making minerals is mica, and a typical example of a schist is one composed of mica and quartz in which mica is the chief cleavable mineral. Such a rock may therefore be called a mica-quartz-schist. There is great variation in the approach to perfection of the arrangement of the minerals. For instance, the plates of mica may be almost perfectly straight and parallel or they may be curved or even crenulated. The closest approximation to the above definition of schist is that given by Geikie. According to this author, "A rock possessing a crystalline arrangement into separate folia is in English termed a schist."[a] It is to be noted that the definition of schist given is

[a] Geikie, Archibald, Text-book of Geology, Macmillan & Co., London, 3d ed., 1893, p. 178.

purely structural, and to its structural meaning the term will be rigidly confined in this treatise.

However, the term schist has been widely used both in a structural sense and as the name of definite rocks; and indeed this double usage is found even in Geikie, whose definition restricts the term to a structural meaning. Illustrations of the use of the term schist both as the name for a definite rock and with a structural signification are furnished by the terms mica-schist, chlorite-schist, and hornblende-schist as generally used. In the case of mica-schist, the term means that the rock is a schistose mica-quartz rock. As here proposed such a rock should be called a mica-quartz-schist. The omission of the term quartz from the name of this rock arose naturally, since this is one of the most abundant varieties of schists, and since in it mica is so conspicuous and quartz so inconspicuous. After it was discovered that quartz is usually equally or more important than mica in most schists, usage came to imply the presence of quartz in the rock called mica-schist. But as the study of rocks continued, other schists were found in which the conspicuous constituent is not mica, but chlorite or hornblende; and such rocks were immediately called chlorite-schists or hornblende-schists, the implication being that quartz was the remaining chief constituent However, when close microscopical studies were begun, they showed that in the chlorite-schists and hornblende schists quartz might or might not be an abundant constituent, its place being taken by feldspar or other minerals, and thus chlorite-schist or hornblende-schist, as used by most English-speaking geologists, means a schistose rock containing chlorite or hornblende and other unnamed minerals. Thus the original scheme broke down. The German petrographers soon saw this, and where schistose rocks were found in which feldspar was an important constituent they proposed to call the rock a gneiss, since feldspar was recognized as an important constituent in the rocks which had before been called gneiss. When the English and American geologists ascertained that a schist, as they use the term, might contain various combinations of minerals, they were inclined to return strictly to a structural sense, as indicated by the quotation from Geikie already made. But as yet this plan has not been carried out consistently in reference to individual rocks, and the usage of combining a structural meaning with mineralogical implications is still common. It seems to me that clear discrimination can be obtained only by restricting the term schist to the

structural meaning as advocated. Illustrating the usage, if a rock which has the structural characters of schists as here defined be composed of hornblende and plagioclase as chief constituents, it is a hornblende-plagioclase-schist. If the plagioclase be definitely determined, as, for instance, labradorite, such a rock is a hornblende-labradorite-schist; and of course the classical mica-schist is mica-quartz-schist, as already stated.

The schists in which it is not desired to direct the attention to their origins, or the origins of which are not known, are thus satisfactorily discriminated by mineralogical qualifiers. If the origin of a given schist be known, and it is desired to indicate this, the term is used in precisely the manner in which it is proposed to use slate, viz, by combining schist with the names of rocks from which it has been derived. In doing this either the schistose character or the origin of the rock may be emphasized. If it be desired to emphasize the schistose character, and at the same time to indicate the original rock from which the schist is derived, the name of this rock may be prefixed. For instance, if a schist be derived from arkose, it is an arkose-schist. If a schist be derived from a gabbro, it is a gabbro-schist. If it be desired to emphasize the original rock from which the schist is derived, and only secondarily to indicate that the rock has a schistose character, this may be done by placing the word schist in the first position; as, for instance, schistose arkose or schist-arkose, schistose gabbro or schist-gabbro. Finally, if it be desired to combine the chief minerals with the compound names which indicate the schistose character and the origin of the rock, this may be done. For instance, a rock may be said to be a mica-quartz-feldspar-arkose-schist.

The usage above advocated is very advantageous in handling the metamorphosed rock masses, since the mineral character of a given schist may be correctly indicated without any reference to its origin, or the origin of the schist may be very accurately indicated. If the term schist be used with a combined structural and mineralogical meaning, as is ordinarily done, such usages are impossible. For instance, if schist means the presence of a certain mineral, as quartz, it can not be applied to a rock which has a schistose character as here defined and which does not contain quartz. For example, one could not say peridotite-schist. Considering all the foregoing facts, the advantage of restricting the term schist to a purely structural usage is so great that all mineral implications for the term should be dropped.

GNEISS.

The term gneiss is defined to apply to a banded rock the bands of which are petrographically unlike one another and consist of interlocking mineral particles. The bands in different gneisses are of variable thickness, ranging from a fraction of a centimeter to many centimeters. Also there is a similar range in thickness of the different bands of the same gneiss. The lithological dissimilarity of the bands of gneiss constitutes a fundamental distinction between gneisses and the slates and schists, which are comparatively homogeneous. Usually the gneisses have a cleavage parallel to the banding, but this cleavage is by no means so general or distinctive as in the slates and schists, and not infrequently a parallel arrangement of the mineral particles resulting in cleavage is almost wholly lacking. This is especially likely to be the case with the gneisses of igneous origin. It has been explained that the slaty and schistose structures are mainly dependent upon recrystallization during mashing. (See pp. 688–690, 748–759.) Where a parallel arrangement of the mineral particles is marked in gneiss this is likely to be largely due to the same cause. But the parallel orientation of some of the mineral particles of a part of the original gneisses formed from magmas is due to differential stress during the primary crystallization of the rocks.

The use of the term gneiss advocated in the preceding paragraph approximates closely to the practice of American and English geologists in recent years. But gneiss, like schist, has been extensively used with a dual meaning, comprising structural and mineralogical factors. For instance, in Germany the word gneiss has been used generally to designate rocks which have the structure either of schists or of gneisses, as defined in the foregoing pages, and which have a quartz-feldspar background with one or more other constituents. In this sense the terms mica-gneiss and hornblende-gneiss mean rocks having either a schistose or a gneissose structure, as here defined, and a quartz-feldspar groundmass in which are respectively mica and hornblende. The dual significance of the term gneiss has arisen naturally from the fact that many of the gneisses, especially the abundant ones first studied, have as chief constituents quartz and feldspar, and with these minerals one or more other constituents. The minerals quartz and feldspar common to them were taken as distinctive of the gneisses, and the names of the other minerals were prefixed as qualifiers. But precisely as is the case

with schists, the term gneiss was extended to banded rocks many of which do not have this definite mineral groundmass. This became apparent only when the microscope was applied to thin sections of rocks.

Since, as a matter of fact, it has been found that the rocks which have been called gneiss have a very great variety of mineral constituents, and not necessarily any of the constituents originally supposed to be implied by the name, it is no longer possible to use the term gneiss with a dual signification and at the same time to have clear discrimination. I therefore propose to confine the term gneiss strictly to its structural sense, including all finely banded crystalline rocks, whether of igneous or of aqueous origin. Thus defined, the term gneiss may be applied precisely as are the terms slate and schist. Mineralogical qualifiers may be prefixed; the name of the rock from which the gneiss is derived may be prefixed; the word gneiss may be prefixed to the name of the original rock; and, finally, names denoting the mineral composition, the name of the original rock, and the term gneiss may be combined. For instance, we may say mica-quartz-feldspar-gneiss, diorite-gneiss, granite-gneiss, gneissoid diorite, gneiss-diorite, gneissoid granite; gneiss-granite, and finally mica-quartz-feldspar-gneiss-granite, etc.

GENERAL STATEMENTS.

It has been seen that all of the terms which have been discussed—*meta*, *apo*, slate, schist, and gneiss—may be united with petrographical names and with mineralogical qualifiers in various ways. For additional refined discrimination geographical qualifiers may be used.

Under the usages advocated the character of a metamorphosed rock may be designated very loosely and broadly either in a structural or in a petrographical sense, may be discriminated with a moderate degree of accuracy, or may be designated very accurately. The following usages illustrate the various stages of gradation from loose to accurate designation: An original unaltered rock may be granite, diorite, syenite, limestone, sandstone, etc. If we wish to indicate that the rock has been altered without saying anything as to the nature of the alteration, we may prefix *meta* to these terms. If alteration has taken place, but the original texture of the rock is retained, we may prefix *apo* to any of the names. If alteration has taken place so as to produce new structures, we may prefix to the names the words slate-, schist-, or gneiss-, or the adjectives slaty,

schistose, or gneissose. If we wish to designate the minerals of which the rocks are composed, we may prefix the names of the minerals to any of the previous names, as, for instance, mica-hornblende-schist-syenite, or mica-hornblende-syenite-schist. Still further accuracy is obtained by prefixing a geographical name, as Aurora granite. A final stage of accuracy is obtained by combining all of these devices, as Aurora mica-quartz-feldspar-schist-granite, or Aurora mica-hornblende-syenite-gneiss. Of course ordinarily the rock will be designated by the simpler terms, but somewhere in a paper all of the qualifiers can be put together, so as to give in a single compound name its most accurate designation.

The elasticity of this plan, by which it is possible to make loose, approximate, and very fine discriminations, is noteworthy. In the field it may not be possible to give the mineral composition or the origin of the rocks and an expression on these points can be avoided. But so far as the facts are known they may be expressed in the notes if desired. Thus all grades of knowledge of the metamorphic rocks can be indicated without implying more than is known. When additional knowledge is gained and further refinement is possible, these refinements may be expressed.

In preparing reports in the office it is very often advantageous to be able to throw large groups of rocks together which have common structures or textures without reference to their mineral composition or origin. In another part of the text it may be desirable to indicate the mineral character of the different rocks. In other parts of the text it may be desirable to indicate exactly the origin of the rocks. All these wants are very nicely met by the proposed usage of the terms meta, apo, slate, schist, and gneiss.

SEDIMENTARY ROCKS.

The sedimentary rocks may be divided in accordance with the ordinary classification into nonfragmental or nonclastic and fragmental or clastic.

The nonfragmental rocks may be divided into five orders—nitrates, sulphates, chlorides, carbonates, and oxides. The only important nitrate is niter. The important sulphates are gypsum and anhydrite. The only important chloride is rock salt. The carbonates may be divided into two families—the calcium-magnesium carbonate family and the iron-bearing carbonate family. The oxides are divided into two families—the iron-oxide family and the silica family.

Following Naumann and Haüy,[a] the fragmental rocks are divided into three orders—psephites (ψῆφος, a pebble), psammites (ψαμμός, sand), and pelites (πηλός, clay). The psephites include the fragmental rocks which contain abundant fragments coarser than peas. Frequently the matrix of the psephites is psammitic. The psammites, following Rosenbusch,[b] are defined as including the sedimentary rocks which are composed of particles under the size of peas and larger than dust. The pelites are composed of the minute particles, from those of the size of dust down.

The unconsolidated psephites, depending upon the coarseness, may be called pebble, gravel, or bowlder deposits. Since the psephites are unassorted material, the order includes but this one family and their metamorphosed equivalents.

The psammite order comprises three families—quartz sands, quartz-feldspar sands, and ferromagnesian sands, and the metamorphosed equivalents of each.

The pelite order includes but one family—the muds, and their metamorphosed equivalents.

The foregoing classification may be represented in tabular form as follows:

Classification of sedimentary rocks.

Class.	Order.	Family.
Nonfragmental	Nitrates	Niter.
	Sulphates	Gypsum and anhydrite.
	Chlorides	Rock salt.
	Carbonates	Calcium-magnesium carbonates.
		Iron-bearing carbonates.
	Oxides	Iron oxide.
		Silica.
Fragmental	Psephites	Pebble, gravel, and bowlder deposits and their metamorphosed equivalents.
	Psammites	Quartz sands. (And their metamorphosed equivalents.)
		Feldspar-quartz sands. (And their metamorphosed equivalents.)
		Ferromagnesian sands. (And their metamorphosed equivalents.)
	Pelites	Muds and their metamorphosed equivalents.

[a] As cited by Zirkel, F., Lehrbuch der Petrographie, Leipzig, 1893, vol. 1, pp. 493–504.
[b] Rosenbusch, H., Elemente der Gesteinslehre, Stuttgart, 1898, pp. 386–389.

The foregoing classification is made upon the basis of giving family names to the abundant kinds of the sedimentary rocks. If names were provided for kinds which are not abundant, a multitude of names would be necessary. The intermediate varieties may be provided for by compounding the various names within either the fragmental or the nonfragmental class. If the materials of each of the two classes be about equally abundant, the names may be hyphenated; if one is subordinate, this may be used in the adjective form. The following illustrates the usage: If a rock is about halfway between shale and limestone, it may be called a shale-limestone or limestone-shale. If the fragmental material be subordinate, it may be called shaly limestone. If the nonfragmental material be subordinate, it may be called a calcareous shale. In a similar manner, if a rock be intermediate between the carbonate and siliceous rocks, one may say limestone-chert, chert-limestone, or calcareous chert, cherty limestone. If it be desired to indicate still more closely the character of the rock, geographical names may be prefixed.

It thus appears that the classification of the sedimentary rocks is comparatively simple, since, as explained on pages 555–560, the sorting of the sedimentary material, both mechanically and chemically, is along definite lines, and consequently large masses of material are produced which have comparatively narrow ranges in composition, and these abundant rocks are selected for the family names. However, the fact must not be forgotten that there are all gradations between all varieties of the sedimentary rocks. The law that gradation is the rule in nature is no better illustrated than by the sedimentary rocks. In biology, while gradations have once existed between various forms, in many cases the intermediate forms have been destroyed. In the early days of petrography it was not supposed that between the various igneous rocks gradation existed. But gradation varieties are known between the more important facies, although gradational varieties between all kinds have not yet been discovered. But the fact that each kind of sedimentary rock grades into the related kinds has been recognized since the rise of geology, and thus there has been no such confusion and multiplication of names for the sedimentary rocks as for the igneous rocks. While gradations between the different varieties of the sedimentary rocks exist, it is believed that under the families above named probably 90 per cent or more of the

material of the sedimentary rocks may be placed, and, as already explained, the remaining 10 per cent is provided for by compound names.

We are now prepared to consider the manner of formation of the various families of original sedimentary rocks, their transformation, and resultant alteration forms.

NONFRAGMENTAL CLASS.

NITRATE ORDER.

NITER FAMILY.

Natural niter is mainly soda niter ($NaNO_3$), although potash niter (KNO_3) does occur in subordinate quantity. The sodium and potassium of the niter are mainly derived from the many alkaline-bearing silicates by their decomposition in the zone of katamorphism, and chiefly in the belt of weathering, through the process of carbonation. The original source of the nitrogen of the niter is the atmosphere. This is oxidized in the zone of katamorphism, mainly in the belt of weathering and very largely in the soil, to nitric acid. (See Chapter VI, pp. 465–466.) The nitric acid unites for the most part with the alkalies, forming the nitrates. The nitrates, once formed, are dissolved from the soils by the circulating ground water and carried to the sea or to lakes with no outlets. In the lakes niter is chemically precipitated in consequence of continual addition of salts in solution and evaporation of water. Niter is the most readily soluble of the important natural salts, and therefore is the last of the series of chemical precipitates to separate. It forms in the final stages of desiccation of the lakes as the top deposit. Therefore niters are wholly the products of the zone of katamorphism, and mainly of the belt of weathering.

The most extensive known deposits of niter are those in the extremely arid regions of Chile. Niter deposits also occur in Bolivia, in Nevada, and in southern California.

The alterations of niter are those of recrystallization and solution. The process of recrystallization need not be dwelt upon, as it is in no way different from the recrystallization of other readily soluble compounds. Niter is so readily soluble that, unless the region be one of extreme aridity, the rock, after having been precipitated, is redissolved and transported elsewhere. Even where niter becomes buried under other rocks, it is likely to be dissolved by the ground waters and again brought to the surface. Consequently niter as a deeply buried rock is rare.

SULPHATE ORDER.

GYPSUM AND ANHYDRITE FAMILY.

Gypsum is hydrated calcium sulphate ($CaSO_4.2H_2O$). Anhydrite is calcium sulphate ($CaSO_4$). The calcium for gypsum is released from other combinations, mainly silicates, in the zone of katamorphism, and especially in the belt of weathering. Sulphur, as sulphide, and especially as pyrite, is a widespread but not abundant mineral in the original igneous rocks. In the zone of katamorphism, and especially in the belt of weathering, the sulphur is oxidized to sulphuric acid. The sulphuric acid unites with bases and forms sulphates. Sulphates formed in the belt of weathering are transported by the underground circulating waters to the sea or to lakes without outlets. In these lakes, by the continual addition of sulphates and evaporation, supersaturation is reached, and the sulphates are thrown down as calcium sulphate, because this is the most insoluble of the sulphates of the bases which abundantly occur in such bodies of water. Where locally barium and strontium are found, these sulphates form in preference. Gypsum is less soluble than niter and sodium chloride, and more soluble than calcium carbonate; therefore it is mainly precipitated after the tufas and before the rock salts. Gypsum is now forming on a somewhat extensive scale in lakes with no outlets. In the past it has formed on a very extensive scale in such lakes and has been buried under later deposits. Some of the more important gypsum deposits of the United States are those of Grand Rapids, Michigan, and Fort Dodge, Iowa, and the widespread gypsums which occur in connection with the Red Beds (Permian and Triassic) of western America.

Gypsum, like rock salt, may by recrystallization become coarsely crystalline. In many localities, because of its somewhat ready solubility, it has formed crystals of great size. The most famous of the localities for large gypsum crystals is that of the Paris Basin. However, the most gigantic crystals known have recently been discovered in Utah, some of them measuring 150 cm. in greatest dimension.[a]

Gypsum, like niter and rock salt, is a product of the zone of katamorphism, and mainly of the belt of weathering.

When gypsum beds become so deeply buried that pressure is dominant, and the heat is somewhat higher than at the surface, the process of dehy-

[a] Talmage, J. E., A remarkable occurrence of selenite: Science, vol. 21, 1893, pp. 85–86.

dration occurs, and thus gypsum passes into anhydrite, with a decrease of volume of 38 per cent. Anhydrite is then a result of the dehydration of gypsum, often in the zone of anamorphism. But it is to be remembered that after a deposit of gypsum has been changed to anhydrite in the lower zone, in order that it shall reach the surface by denudation it must pass through the upper zone, and under these conditions hydration occurs to a greater or less extent, and it is thus transformed to gypsum in part or in whole. At various localities the beds of calcium sulphate are in part composed of gypsum and in part of anhydrite. Doubtless in places where the deposits are deep the change toward anhydrite is taking place, and in other places near the surface the change toward gypsum is taking place.

CHLORIDE ORDER.

ROCK-SALT FAMILY.

Rock salt, impure sodium chloride, or simply salt, is the only abundant chloride. But potassium chloride, calcium chloride, and magnesium chloride are found as impure compounds. The sodium is derived mainly from the silicates. It is liberated from these compounds in the zone of katamorphism, mainly in the belt of weathering, by the process of carbonation. The chlorine is more difficult to account for. Of the minerals in the original rocks, only sodalite, wernerite, and apatite contain chlorine. But sodalite is abundant in the soda rocks, and the last two minerals are very widespread. Therefore these minerals are an important source of chlorine. It is well known that hydrochloric acid and other chlorine compounds are emitted in large quantities in connection with volcanic action. In this connection it should be noted that at periods of regional volcanism the quantity of chlorine emitted is vastly greater than during periods of local volcanism, like the present.[a] It has been supposed that emissions of chlorine during volcanism are evidence that sea waters from the surface, or the salts of underground solutions, have penetrated to the roots of volcanoes, and thus contributed chlorine to magmas. Doubtless this is true in some instances, but it can not be assumed from occasional cases of this kind that the chlorine very generally emitted in volcanic regions is thus derived from the zone of

[a] Van Hise, C. R., Earth movements: Trans. Wisconsin Acad. Sci., Arts, and Letters, vol. 11, 1898, pp. 496–497.

katamorphism. I believe that much of the chlorine emitted from volcanoes is not thus derived, but is an original constituent of the deep-seated magmas, and it follows that before the crystallization of the magmas a portion of the chlorine escapes. Consequently the quantity of chlorine in the crystallized igneous rocks is less than originally existed in the magmas. Probably the original chlorine minerals and the emissions in connection with volcanism are sufficient to account for the chlorine of the chlorides.

Sodium chloride formed in the soil is taken into solution and is transported to the sea or to lakes with no outlets, which are prevented from expansion by evaporation. As the process continues salt accumulates to the point of saturation, when further evaporation leads to chemical precipitation, precisely as with niter.

Sodium chloride ranks in solubility next to niter, and is abundantly precipitated before the latter compound is. Deposits of rock salt are forming in various desert regions at the present time by the evaporation of the waters of inclosed seas, such as the Dead Sea, Great Salt Lake, etc. Extensive deposits formed under similar conditions during past geological periods have been buried under later formations, and these are the rock-salt beds. Illustrations of such deposits are the thick rock-salt formations of Poland, of central Germany, and of Louisiana. From the foregoing it is plain that rock-salt deposits are strictly products of the zone of katamorphism, and mainly of the belt of weathering.

The alterations of rock salt are those of recrystallization and solution. In some cases the material has become coarsely crystalline, as in the case of the Polish deposits. In order that a rock-salt formation shall be preserved it is necessary that it be buried under relatively impervious formations, in order that the underground circulation shall not be so rapid as to dissolve the material and bring it to the surface. That solution of many ancient deposits is taking place is shown by the briny waters which are found at many localities. Where such ground waters issue at the surface we have salt springs. Such salt springs were known in America in early days as "salt licks," because the animals frequented these places in order to lick the salt which was deposited. As illustrations of deposits which are being dissolved and which are artificially abstracted from the earth in the form of brine, those of the Saginaw district of Michigan and the Syracuse district of New York may be mentioned.

CARBONATE ORDER.

CALCIUM-MAGNESIUM CARBONATE FAMILY AND METAMORPHOSED EQUIVALENTS.

The calcium-magnesium carbonate family, with its metamorphosed equivalents, comprises limestone, dolomite, marble, cherty limestone, cherty dolomite, and cherty marble, silicated marble, and silicate rocks. Each of these will be considered in turn.

LIMESTONES.

Limestones comprise all those rocks which are mainly composed of calcium carbonate ($CaCO_3$).

SOURCE OF MATERIAL OF LIMESTONES.

The original dominant source of the calcium and magnesium of the calcium-magnesium carbonates is mainly the many alkaline earth-bearing silicates. The silicates are decomposed in the zone of katamorphism, and very largely in the belt of weathering, by the processes of carbonation, hydration, and oxidation. So far as the process is due to carbonation the carbonates are formed directly. In so far as the bases are set free by other reactions they may later unite with the carbon dioxide. The carbon dioxide immediately concerned in the process of carbonation is mainly derived directly from the atmosphere, from that produced by the oxidation of the organic compounds, by the liberation from rocks during their decomposition of inclosed carbon dioxide, and from the deep-seated waters rising from the zone of anamorphism. (See pp. 461–465, 473–475, 608–610, 667, 677–678.) The relations of these sources of carbon dioxide to one another and the replenishment of the supplies in order to carry on the process of carbonation are fully discussed in Chapter XI, under the heading "Carbon."

The calcium and magnesium unite with the carbonic acid formed and form carbonates. The original carbonates are solely produced by the reactions of the zone of katamorphism, and chiefly by reactions of the belt of weathering.

The calcium carbonate formed as above described, after transportation to the sea or to lakes with no outlets, is thrown down as organic precipitates and as chemical precipitates, and thus limestone is formed.

ORGANIC PRECIPITATES.

Animals of the ocean and lakes abstract calcium carbonate from solution and build it into their hard parts. The number of kinds of organisms which are doing this work is great. Of these the more important classes are the corals, mollusks, and crinoids, the relative importance probably being in the order given. In each class are many species, and the number of individuals of each species is beyond computation. In order that a great quantity of material may be abstracted from the water by organisms it is necessary that abundant material shall be furnished to it, and also that the conditions shall be favorable for the existence of abundant animal life of the right kind. The material for the building of limestone is furnished to the ocean mainly by the streams. Therefore, adjacent to great bodies of land from which large rivers enter into the sea there is a continuous and abundant supply of calcium carbonate. Sluggish rivers which have meandered through limestone regions furnish an especially abundant supply. An essential condition for abundant animal life in the sea is a warm climate, and hence the limestones are likely to be formed most plentifully in the tropical or subtropical regions. Tropical and subtropical regions are favorable for limestone building for the further reason that evaporation is great and concentration of calcium carbonate is thus produced. This is of great importance in shallow, nearly inclosed seas, and lagoons. The areas which combine the two conditions—abundance of material and abundance of life—are those in which the great limestone building of the present time is going on. Such regions are illustrated by Florida and the Bahamas, the sea adjacent to which is constantly fed by the currents from the Gulf of Mexico, which receives the great contributions of calcium carbonate of the Mississippi and many other rivers; and by the regions adjacent to the Yellow Sea, which receives the contributions of the Yangtze, Hoangho, and many other important rivers. But the immediate contributions of great rivers are not necessary for extensive limestone formations, for the ocean currents distribute material throughout the seas, and the water contains a sufficient amount of calcium carbonate, so that where other conditions are favorable extensive limestone formations may be built. This is illustrated by the Great Barrier Reef of Australia and the numerous coral reefs about the tropical islands of the Pacific.

The material deposited by animals may be amorphous or crystalline aragonite or calcite. The material deposited by corals and crinoids is crystalline, and is in the form of aragonite; the material deposited by the mollusks is in the form of calcite, and to a less extent of aragonite. The continuous precipitation of calcium carbonate of the sea by organisms, and the building up of organic deposits through geological periods, combined with mechanical rearrangement and with recrystallization (see pp. 795–797), result in the great limestone formations.

CHEMICAL PRECIPITATES.

Chemical precipitates of calcium carbonate include the deposits of springs and streams; inland seas with no outlets, like the Dead Sea, Great Salt Lake, etc.; and possibly chemical precipitates in the ocean or in seas connected with the ocean.

Springs and streams.—Tufa deposits are frequently formed by streams just after issuing from underground, and they are formed from water in caves as it issues from the confined passages into the open caverns. In both these cases the causes of the supersaturation and precipitation are the same—release of pressure, with escape of carbon dioxide, and evaporation. Spring and stream deposits of tufa are usually small and unimportant.

Inland seas with no outlets.—In inland seas with no outlets the calcium carbonate contributed by the streams steadily accumulates. On the average, evaporation balances the additions of water. Concentration of the calcium carbonate is the result, until supersaturation follows, and finally precipitation. These deposits have generally been called tufa, and they are finely illustrated by the deposits of the ancient lakes Lahontan and Bonneville. Such deposits are forming at the present time in Salt Lake, Pyramid Lake, Walker Lake, and Winnemucca Lake.[a] The tufa forming in lakes and inclosed seas is likely to be rather impure in consequence of the simultaneous precipitation of other compounds, especially sodium chloride and gypsum.

Possible chemical precipitates in the ocean or in seas connected with the ocean.—Willis holds it to be extremely probable that extensive limestone formations have been chemically precipitated in the sea.[b] At the present time the ocean and the

[a] Russell, I. C., The geological history of Lake Lahontan: Mon. U. S. Geol. Survey, vol. 11, 1885, pp. 188–223. Gilbert, G. K., Lake Bonneville: Mon. U. S. Geol. Survey, vol. 1, 1890, pp. 167–169.

[b] Willis, Bailey, Condition of sedimentary deposition: Jour. Geol., vol. 1, 1893, pp. 519–520.

connected seas are not saturated with calcium, or even approximately so. According to Mendeléeff,[a] 1 kg. of water saturated with carbon dioxide will dissolve 3 grams of calcium carbonate. The amount of calcium carbonate in the ocean at the present time, per kilogram of water, is .11869 gram, or 3.956 per cent of the above amount;[b] but since sea water is not saturated with CO_2, the amount of calcium carbonate which could be held is less than 3 grams per kilogram. It is certain that under present conditions the precipitation of calcium carbonate from the ocean is mainly accomplished by organisms, as explained on pages 792–793. But in early geological periods, before life was abundant and great quantities of calcium carbonate were extracted from the sea by animals, it is barely possible that supersaturation occurred and chemical precipitation resulted. Supersaturation could have been brought about by two factors: First, steady additions of calcium carbonate from the land in connection with evaporation from the sea produced concentration. Second, it is possible that the amount of carbon dioxide in the atmosphere, and therefore in the ocean, was greater then than at present. As the carbon dioxide in the atmosphere was used up by the processes of carbonation, carbon dioxide would pass from the ocean to the atmosphere, and a decrease in the amount of this compound in solution would result in chemical precipitation of the calcium carbonate.[c]

The two causes for precipitation considered apply to the entire body of the ocean. Precipitation caused by them alone would be very widespread, if not universal. The theory of chemical precipitation in the ocean has greater plausibility if there be combined with the two previous causes the existence of partly inclosed tropical mediterranean seas, which received great contributions of materials from large rivers and lost great quantities of water by evaporation. Under these circumstances chemical precipitation might occur without premising saturation of the entire ocean. It is therefore theoretically possible that extensive limestone deposits were produced by chemical precipitation in early geological ages. But if the ocean as a whole did at any time contain enough calcium carbonate to saturate it, or even enough to nearly saturate it, the subsequent process of limestone building by

[a] Mendeléeff, D., The principles of chemistry, trans. by Geo. Kamensky, Longmans, Green & Co., London, 1897, vol. 1, p. 592.

[b] Dittmar, William, The composition of ocean water: Report of the Scientific Results of the Exploring Voyage of H. M. S. *Challenger*, 1873–76; vol. 1, Physics and Chemistry, 1884, pp. 2, 204.

[c] Mendeléeff, cit., vol. 1, p. 592.

organic precipitation must have more than equaled the additions of calcium carbonate from the land, and thus have reduced the total amount in solution.

In the present state of knowledge it must be said that the precipitation by chemical means of great limestone formations in the ocean, or in mediterranean seas connected with the ocean, is a speculation based upon the premised inadequacy of life in early times to precipitate such amounts of materials, and is required to explain only the limestones of pre-Paleozoic times, the rocks of which contain very scanty fossils. But even these limestones may have been precipitated by organisms and the fossils destroyed by the processes of recrystallization and metamorphism subsequently described, just as they have been in many later formations.

METAMORPHISM OF ORGANIC AND CHEMICAL CALCIUM CARBONATE DEPOSITS.

During the time that the various forces and agents are abstracting the calcium carbonate from the sea the mechanical and chemical forces are at work. No sooner is a deposit formed than the waves may break it into detritus. All the organic and chemical deposits within the reach of the waves and currents are handled by them. Thus, the material may be widely distributed according to the laws of the distribution of mechanical deposits. (See Chapter VI, pp. 555–560.) To illustrate: The débris of the coral reefs is carried seaward until the water reaches such a depth that the undertow has lost its power. Thus conglomerate, sand, and silt composed of limestone may be deposited in concentric belts. (Pl. IV, *A*.) Any of the shore deposits described by Gilbert may be built up.[a] But the mechanical work does not go on alone. The moment an animal dies the calcium carbonate is subjected to the action of solution and deposition by the sea. When the material is exposed to the open sea, or when there are continuous currents, the water is not saturated with calcium carbonate, and there is continual solution of the material at the rock surface. Within the body of the rock the particles may be cemented by deposition. (Pl. IV, *B*.) In inclosed or nearly inclosed areas, as, for instance, locally between the islands and reefs encircling Australia, the evaporation may more than compensate for the influx of fresh water, and thus the tendency, on the whole, be to precipitate additional material from the sea, rather than to dissolve material.

At the same time limestone is forming there may be a substitution of magnesium for calcium. The processes of solution and redeposition and of

[a] Gilbert, G. K., Lake Bonneville: Mon. U. S. Geol. Survey, vol. 1, 1890, pp. 23–89.

substitution are fully considered below, in treating of "Recrystallization" and "Dolomitization." The amount and speed of the recrystallization depend, of course, upon many factors. Rather ancient limestones may have been only partially recrystallized. On the other hand, the limestones now forming may locally be coarsely crystalline.

Commonly the mechanical and chemical forces work together in the rearrangement of the rock. This is finely illustrated among the lagoons of Florida and Australia. In these regions abundant life is building up calcium-carbonate deposits. The deposits are being broken up by the waves; they are being taken into solution by the sea; evaporation is going on; and redeposition is occurring within the deposits. Thus in these regions, while the first precipitation takes place as a consequence of the action of the animals, the mechanical and chemical forces immediately begin to rearrange the calcium carbonate into a detrital rock cemented by calcite, or into coarsely crystalline rocks entirely dissolved and redeposited by means of the chemical forces, or into a combination of these.

Saville-Kent describes the main mass of the material upon which the Australian corals are at present building their deposits as limestone conglomerates, largely built up of the cemented débris of corals and mollusks.[a] (Pl. IV, *A*.) The breaking of the Barrier Reef is due to the waves; the cementing of the material he attributes to evaporation during the low tide, when the surface is above water, at which times the sun evaporates a large amount of the interstitial water, and thus deposits material. It may be supposed that this process is continuous, material being added to the solutions at each time of high water and deposited at each time of low water. But it may be doubted whether it is necessary for the reefs to be exposed in order that consolidation shall occur. It seems highly probable that in the ocean menstruum the limestone débris are consolidated by the chemical processes of solution and deposition, even if the material remains continually below the surface of the water.

The process of recrystallization does not cease when the limestone formations are raised above the sea. When these formations constitute land, recrystallization continues under both mass-static and mass-mechanical conditions. This is accomplished by the action of the underground waters It has been fully explained that in its movement water is continually taking material into solution and is continually depositing material from solution.

[a] Saville-Kent, W., The Great Barrier Reef of Australia, London, 1893, pp. 52–54.

A

B

C

TEXTURES OF LIMESTONES AND MARBLE.

Further, it has been explained that in the belt of weathering solution is the rule, and that in the belt of cementation solution does not so far surpass deposition but that cementation is the rule. No other rock so well illustrates these principles as limestone, for it is the most readily soluble of the extensive formations. Under the law of dominant solution in the belt of weathering the openings are enlarged, and thus the very numerous cracks, crevices, and caves, great and small, so characteristic of limestone, are formed. But while solution dominates in the belt of weathering, as shown by these openings, deposition is, as explained on page 487, an invariably accompanying process. Thus are made the stalactites, stalagmites, and travertine deposits. These deposits may be either aragonite or calcite.

In the belt of cementation below the level of ground water in limestones the openings formed in various ways are as generally decreased in size by deposition as they are enlarged in the belt of weathering. The material here deposited is generally in the stable form of calcite.

But the process of solution and deposition in the belt of weathering and the belt of cementation does not affect the walls of the openings only. Solution and deposition are going on continuously throughout the entire mass of limestone formations in the zone of katamorphism. As a consequence of this the rock is continuously recrystallized. This process, even under mass-static conditions, may advance so far as to transform a limestone into a uniformly crystalline rock, to which the term marble is applicable. However, where the recrystallization goes so far as to transform the rock to a marble, there has usually been more or less mechanical action. But the consideration of the marbles is deferred. (See pp. 808–816.)

In modern limestones fossils are likely to be abundant; in ancient limestones they are comparatively sparse. In general it may be said that they are less abundant as the rocks are old. Also, in proportion as the rocks are old they are likely to be well crystallized. The increased sparseness of fossil remains and the crystalline character of the limestone may both be regarded as evidence that recrystallization has taken place. Also they might be interpreted as evidence that life was not so abundant in the past and that the material had been deposited as a chemical precipitate. But certainly the latter argument does not apply to rocks later than the Algonkian. Since fossils so commonly constitute but a small fraction of the present mass of limestones, it is concluded that recrystallization has extensively occurred in Paleozoic and post-Paleozoic limestones. (See Pl. VI, *A*.)

DOLOMITE.

ORIGIN OF DOLOMITE.

Dolomite is calcium-magnesium carbonate ($CaCO_3.MgCO_3$). In considering the origin of dolomite the questions immediately arise: Are magnesian limestones and dolomites originally deposited as such, or are they the results of replacement of calcium by magnesium? and, if the latter, how and when did the process take place?

Dolomite due to replacement of calcium by magnesium.—That the magnesium carbonates are due to replacement of magnesium for calcium, and therefore to dolomitization, seems to be conclusively shown by the following considerations:

(1) The first of the various lines of evidence in favor of dolomitization is the composition of the hard parts of sea animals. We do not know any sea animals which deposit more than a small amount of magnesium carbonate in their hard parts. Forchhammer analyzed a large number of corals and shells of marine animals. In bivalves he found the amount of magnesium to vary from 0.5 to 1 per cent; in cephalopods he found it to be less than 0.5 per cent. In most corals the amount of magnesium is less than 0.5 per cent, although in one species it is 2 per cent and in another species 6.4 per cent.[a] Sharples analyzed seven species of corals,[b] and does not report magnesium carbonate, although it is to be supposed that a small amount of that compound is present. Forchhammer found[c] in a number of late deposits, which are mainly composed of the remains of animals, that the amount of magnesium is less than 1 per cent. From these results, if it be supposed that formations now dolomitic limestone were originally organic precipitates, it must be concluded either that the magnesium is mainly introduced by a secondary process or that sea animals in early periods used a larger proportion of magnesium for their hard parts than do the present animals. The latter conclusion would be a pure unverified assumption.

(2) Some of those who hold that dolomites are original deposits, in order to escape the difficulty involved in the supposition that animals have

---

[a] Forchhammer, Georg, Bidrag til Dolomitens-dannelshistorie: Oversigt over det Kongelige Danske Videnskab. Forhandlingar, Copenhagen, 1849, p. 89. See also Bischof, Gustav, Chemical and physical geology, London, 1855, vol. 2, pp. 48–49.

[b] Sharples, S. P., On some rocks and other dredgings from the Gulf Stream: Am. Jour. Sci., 3d ser., vol. 1, 1871, p. 169.

[c] Forchhammer, cit., p. 89. Also, Bischof, cit., p. 48.

at some past time secreted magnesium in greater quantities than at present, have held that magnesium limestones and dolomites as such are original chemical precipitates. While the sea is not now saturated with calcium and magnesium salts, it is held that this might have been the case before life became abundant, and that consequently magnesium limestone and dolomite formed directly. This is again a pure, unverified assumption, which seems to be negatived by the following considerations: (a) Since the living animals extract so little magnesium, on this hypothesis it is difficult to explain why the sea is not now saturated or nearly saturated with magnesium salts; (b) Bischof[a] found by experiment that when solutions become saturated with carbonates of magnesium and calcium the calcium carbonate is largely precipitated before the magnesium carbonate begins to be thrown down in appreciable quantity. Hence, by chemical precipitation, there would be produced separate layers composed mainly of carbonate of calcium and carbonate of magnesium, rather than calcium-magnesium carbonate. According with Bischof's experiment, the alkaline earth carbonates precipitated in Lakes Lahontan and Bonneville are essentially calcium carbonate, containing not more than 2.14 per cent of magnesium.[b] The deposits of inland lakes in which the salts accumulate until precipitation occurs should be analogous to those of the ocean in ancient times, on the supposition that before life existed abundantly chemical percipitates formed. The fact that tufas deposited in such lakes contain so little magnesia seems to bear against the hypothesis that the dolomites are original chemical precipitates.

(3) But perhaps the most decisive of the various lines of evidence in favor of secondary dolomitization are observed facts of occurrence which seem to be explicable only upon the basis of replacement. While, as already noted, coral is nearly pure calcium carbonate, Dana found that the limestone of the elevated coral island Metia is heavily magnesian, one specimen containing as much as 38 per cent of magnesium carbonate.[c] Prestwich states that in the Carboniferous limestones of Kilkenny and Cork the upper surface and parts of the rock along the bedding and joint planes

[a] Bischof, Gustav, Elements of chemical and physical geology, trans. by B. H. Paul: Cavendish Society, London, vol. 3, 1859, pp. 169–170.

[b] Russell. I. C., Geological history of Lake Lahontan: Mon. U. S. Geol. Survey, vol. 11, 1885, p. 203. Gilbert, G. K., Lake Bonneville: Mon. U. S. Geol. Survey, vol. 1, 1890, p. 168.

[c] Dana, Jas. D., Corals and Coral Islands, 3d ed., Dodd, Mead & Co., New York, 1890, pp. 393–394.

are often dolomite. Where the rock is dolomite the fossils and the stratification are obscured or destroyed. The deeper lying rock, as well as the rock remote from the joints, is ordinary limestone.[a] Geikie says that essentially the same facts are true on a large scale in the Carboniferous limestone in the north of England.[b]

Spurr describes the limestone of Aspen Mountain, Colorado, as dolomite near the faults. The magnesium becomes less and less plentiful as the distance from the fractures increases. He further states that dolomite almost invariably accompanies the ore.[c] Bain describes precisely similar phenomena in the limestone carrying lead and zinc ore in Iowa.[d] Spurr further finds in the limestone of Glenwood Springs, Colo., old water channels and zones of fracture; and adjacent to these he finds the rock to approach dolomite. Adjacent to the fractures and the underground water channels there is a gradation of the dolomite to the ordinary limestone.[e] Bain states that the Carboniferous limestones of Missouri bearing lead and zinc ore are dolomite in the vicinity of the ore deposits, and elsewhere are largely limestone. He further finds that dolomite is a most important gangue mineral in the openings of the rocks. The fissures connect with the magnesium-bearing Cambro-Silurian limestones below, and he infers that rising waters have transported the magnesium and dolomitized the Carboniferous limestone adjacent to the water channels.[f] Other instances of rapid gradation in the amount of dolomite are furnished by limestones where cut by intrusives. Finally, there are gradual variations in the amount of magnesium in great limestone formations; as, for instance, the great Cambro-Silurian limestone of North America. The Appalachian Valley Cambro-Silurian limestone is a true dolomite, while at various places in the Mississippi Valley the limestone contains so little magnesium as to be merely a magnesian limestone.

The different cases of occurrence of magnesian limestone above given

---

[a] Prestwich, Joseph, Geology—chemical, physical, and stratigraphical, Oxford, 1886, vol., 1, pp. 113–114.

[b] Geikie, Archibald, Textbook of Geology, 3d ed., Macmillan & Co., London, 1893, p. 321.

[c] Spurr, J. E., Geology of the Aspen mining district, Colorado: Mon. U. S. Geol. Survey, vol. 31, 1898, pp. 210–211.

[d] Calvin, Samuel, and Bain, H. F., Geology of Dubuque County: Iowa Geol. Survey, vol. 10, 1900, pp. 492–498, 572–575.

[e] Spurr, cit., pp. 212–216.

[f] Bain, H. F., with Van Hise, C. R., and Adams, G. I., Preliminary report on the lead and zinc deposits of the Ozark region: Twenty-second Ann. Rept. U. S. Geol. Survey, pt. 2, 1901, pp. 208–210.

may be gathered together under a general principle, viz: On the average, limestones in regions of strong orogenic movements, and consequent fracturing, are more strongly magnesian than limestones of equivalent age in less disturbed regions. To illustrate, the Tertiary limestones of the Coast Range of California and of the Alps are more strongly magnesian than the undisturbed limestones of the same age. When the cases of variable magnesium are brought together under this rule, the reason for the variation is plain. Limestones are likely to be magnesian in proportion as there were favorable conditions for the entrance of solutions bearing magnesium, and these conditions are of course furnished by orogenic movements and fractures causing openings. The variations in magnesium content, rapid and slow, above cited, and other similar instances, can apparently be explained only on the theory of secondary replacement.

(4) Taking the world as a whole, the older a limestone formation is the further advanced is dolomitization. Thus the ancient limestones, especially those of Cambrian and Silurian age, are very generally strongly magnesian, and the pre-Cambrian limestones are usually completely dolomitized. This is partly a direct consequence of (3). For in proportion as formations are old they are likely to have been subjected to orogenic movement and to fracture. Also in proportion as they are old sufficient time has elapsed for the other favorable conditions to have occurred. But the principle of increase in dolomitization with age must be broadly applied, for, as already seen, a young formation may be strongly dolomitic in one region, and a much older formation be only slightly dolomitized in another region; also, in various districts heavily magnesian formations occur above limestones containing little magnesium.

(5) It has been shown on page 239 that the change of calcite to dolomite involves a contraction of 12.30 per cent. It is a well-known fact that dolomites which have not been subjected to strong orogenic movement, deep below the surface, are very porous. This is beautifully illustrated by the dolomites of the Mississippi Valley, especially the so-called magnesian limestone series. In this respect the dolomites contrast strongly with the pure limestones. The natural explanation is that the porosity is due to the contraction of the volume as a result of dolomitization. Where the change has taken place in the zone of anamorphism, or where the dolomite has been in the lower zone since the change, mashing and recrystallization have closed the openings.

Conclusion.—From the foregoing facts it is concluded that the major part of the magnesium in dolomitic limestones and dolomites is due to replacement. In the instances of rapid local variation in the amount of magnesium in the limestones of coral islands and in the limestones of England, Ireland, and America, where the amount of magnesium is greatest near the surface or adjacent to fractures, there seems to be no other conclusion. And there is no reason to doubt that the magnesian character of the great dolomite formations is due to replacement.

HOW AND WHY DOLOMITIZATION OCCURS.

The magnesium for dolomitization is primarily derived from magnesium-bearing minerals of the original igneous rocks. The more important of these are the micas, pyroxenes, amphiboles, and olivines. But at the present time a large part of the magnesium for dolomitization is derived from secondary minerals, such as garnet, staurolite, tourmaline, chondrodite, chlorite, the zeolites, and even from previously formed dolomite. Indeed, the magnesium concentrated in earlier dolomite is one of the most important sources for present dolomitization. From these various sources the processes of alteration of the zone of katamorphism, and especially of the belt of weathering, produce soluble magnesium compounds, such as carbonate, hydrate, sulphate, etc. The magnesium compounds formed or dissolved in the belt of weathering are transported in part to the belt of cementation and in part to the sea, either before or after an underground journey. This process has been continuous since the continents were divided from the seas, consequently the amount of magnesium in the sea has probably continuously increased since early geological times, for it can not be supposed that, on the average, more magnesium has been precipitated from the sea than has been added to it during any geological period. It is seen in Chapter X that the amount of magnesium now in the sea is more than three times as great as the amount of calcium.

The process of dolomitization may take place while the limestone is still in the sea or after it has been raised above the sea and constitutes a part of the land.

Dolomitization before limestone emerges from the sea.—The carbonate originally deposited by animals is almost wholly calcium carbonate. The sea contains abundant magnesium salts. Thus we have in the sea a heterogeneous

system (see Chapter III, pp. 90–91), the sea not being saturated with either magnesium or calcium salts, but containing more than three times as much magnesium as calcium, and having below it in various regions solid calcium carbonate. Under these circumstances there is a tendency for some of the calcium of the solid carbonate to change places with the magnesium in solution, and thus dolomitization may take place beneath the sea.

If the sea were saturated with magnesium salts it is probable that the replacement would go on rapidly. Since, however, the sea is far from saturated with such compounds, and since, as already shown (pp. 798–799), it can not be supposed that the sea has ever been richer in magnesium salts than at present, the change has taken place slowly. But the substitution is continuous; for, in consequence of the currents, the water depleted in magnesium is replaced by water containing a normal amount of that element. But the solutions of the ocean also contain calcium. Therefore the conditions are approximately as if one ran magnesium-calcium solutions like those of the ocean through solid calcium carbonate until equilibrium under the laws of chemistry (see Chapter III, p. 90) had been reached. But in the ocean equilibrium is probably but rarely reached on an extensive scale because of the slow and imperfect manner in which the solutions make their way through the calcium-carbonate deposits at the bottom of the sea. Occasionally in the arms or shut-off portions of the sea, where the conditions are favorable for unusual concentration, the amount of magnesium in the water may be even greater than that in the normal waters, and under these circumstances the reaction would go on more rapidly. This is illustrated by the coral reefs of Metia, which are heavily magnesian. This case furnishes positive evidence that dolomitization may locally, under favorable circumstances, go very far while a limestone is below the sea. Dana's explanation of the unusual amount of magnesium is that "the sand or mud may have been that of a contracting and evaporating lagoon, in which magnesian and other salts of the ocean were in a concentrated state."[a] Dana compares concentration of magnesium in lagoons mainly shut off from the sea to concentration in salt pans.[b]

While it is clear that dolomitization below the sea may locally go far, the usual facts of observation correspond with the conclusion above

[a] Dana, Jas. D., Corals and coral islands, New York, Dodd, Mead & Co., 3d ed., 1890, p. 394.
[b] Dana, Jas. D., Manual of geology, American Book Company, 4th ed., 1895, p. 133.

given, that dolomitization below the sea is usually very partial, and that the Metia instance is exceptional. It has already been seen that Forchhammer found that late limestone deposits mainly composed of the remains of animals usually contain less than 1 per cent of magnesium,[a] and that a small content of magnesium is the ordinary thing for late limestones which have not been greatly disturbed by orogenic movements. In view of these facts the question naturally arises as to the time when the dolomitization mainly took place in those extensive dolomite formations in which the magnesium is moderately uniform for a given district, although slowly varying as a whole. The typical formations of this kind in America are the great Cambro-Silurian limestones of the United States, which in the Appalachian region, where deformation is great, are nearly pure dolomites, and which in the Mississippi Valley are often heavily magnesian but rarely dolomite, and show, moreover, rather sharp variations in the amount of magnesium. The hypothesis which one naturally favors, because of its simplicity, is that such formations as these were mainly dolomitized below the sea. But the more closely the facts are examined the less certain does the conclusion appear to be. It is entirely possible that locally the Cambro-Silurian limestone was dolomitized more extensively below the sea than is the case, on the average, for the later limestone formations. Indeed, it has been supposed that this limestone was deposited in a mediterranean sea, and this entire sea may have had to some extent the concentrated conditions at Metia described by Dana. But it appears certain to me, even if the dolomitization was further advanced in the case of some of these formations while below the sea than can be paralleled by recent extensive formations, that they have subsequently been much further dolomitized and the magnesium extensively rearranged since the limestones emerged from the sea.

Dolomitization after limestone emerges from the sea.—While it is clear that the process of dolomitization may take place below the sea, often it is there only initiated. Frequently dolomitization takes place in the main after the limestone becomes a part of the land area and is subject to the forces of metamorphism beneath the air. It is believed that dolomitization in land areas largely occurs in the zone of katamorphism rather than in the zone of anamorphism. The basis of this belief is furnished by the conclusion, fully

[a] Forchhammer, Georg, Bidrag til Dolomitens-dannelshistorie: Oversigt over der Kongelige Danske Videnskab., Forhandlingar, Copenhagen, 1849, p. 89. See also, Bischof, Gustav, Chemical and physical geology, London, 1855, vol. 2, pp. 48–49.

explained on pages 655–656, 764–766, that transfer of material and change in chemical composition are extensive and great in the zone of katamorphism and are trivial and small in the zone of anamorphism. Further, in the zone of katamorphism it is believed that dolomitization mainly occurs in the belt of cementation rather than in the belt of weathering, although the process undoubtedly takes place in both belts.

We have seen that rocks contain magnesium mainly as a silicate or carbonate. If above the level of ground water the magnesium be as silicate, the process of carbonation changes it to a carbonate or other compound, and as such it is taken into solution and carried downward to the sea of ground waters. If the magnesium be as carbonate, the process of carbonation is not necessary. In any case the waters of the belt of weathering steadily carry downward magnesium and calcium carbonate and other salts to the belt of cementation. These solutions pass into limestones and other formations.

When the solutions pass into limestones which contain little magnesium, the process of replacement begins. The substitution of magnesium for calcium is controlled by various factors, among which time, the absolute and relative amounts of calcium and magnesium in the solutions and in the rocks, the change in volume in consequence of the reactions, and the direction of the movement of the solutions are important.

It is certain that time is an important factor. The underground solutions are continually circulating, and there are ever-renewed supplies of magnesium to carry on the process in the solutions which join the belt of cementation. At the outset calcium is greatly predominant in the limestone; but as the substitution goes on, magnesium becomes more and more important, and may finally become molecularly equivalent to calcium. But to accomplish this must require much time, for the solutions at any moment occupy but a small percentage of the volume of the rock, and they contain but a very small amount of magnesium. Therefore the magnesium held at any one time by the solutions is but an inappreciable fraction of the total amount which is finally introduced into the rock.

The absolute and relative amounts of calcium and magnesium in the solutions and the limestones is a matter of the greatest consequence in dolomitization. The law of mass action requires that where solid calcium carbonate is in contact with magnesium- and calcium-bearing solutions a

part of the calcium of the solid be replaced by the magnesium. In a limestone which has been slightly dolomitized the conditions are particularly favorable for dolomitization, for under such circumstances under chemical laws substitution goes on rapidly. But the further the process continues and the nearer equilibrium is approached the slower it becomes. Since, on the whole, calcium is a more abundant base in the sedimentary formations, and also in the ground solutions, than magnesium, and since it is a more energetic base, it follows that at low pressure one could not expect that one-half of the calcium would be replaced by the magnesium, for when the substitution had gone to a certain stage calcium would replace the deposited magnesium as fast as the magnesium replaced the calcium. This stage would usually be reached before the magnesium was molecularly equal to the calcium. In the foregoing we have the explanation of the fact that but very rarely is the magnesium so abundant in extensive formations as to have the precise composition of dolomite.

In determining the stage at which the static condition of affairs is reached pressure is very important. It has been seen that as a result of the substitution of magnesium for one-half the calcium in calcium carbonate there is a contraction in volume of 12.30 per cent; hence pressure tends to promote the change. But pressure increases with depth; therefore the deeper a rock is, the greater is the tendency for magnesium to replace the calcium. Hence in the deeper buried rock, there is a strong force which tends to substitute magnesium for calcium. But the complete substitution is resisted, under the law of mass action, by the greater abundance of calcium, and by the more energetic character of that base. Further, as already pointed out, where the pressure is very great, as in the zone of anamorphism, circulation is very slow, and it is not possible for the solutions to supply sufficient magnesium to accomplish this, and probably in most cases not even enough to change the rock to dolomite. Usually these factors prevent the substitution from going so far as to produce equimolecular quantities of the two elements; but in the case of the pure dolomites this occurs. In such instances it may be that pressure is an important factor. Since few carbonates contain more than an equimolecular amount of magnesium as compared with the calcium, it may be supposed that this compound gives the limiting effect of such pressures as have obtained in the rocks which are within the zone of observation. As a corollary from the

foregoing, one would expect to find dolomites among those rocks which have been deeply buried and strongly deformed, but at the time of dolomitization not so deeply buried as to prevent deformation from producing fractures for circulation, for there, if anywhere, the process of dolomitization would have been nearly completed. With this expectation the facts of occurrence of dolomite as given on pages 798–802 fully correspond.

As to whether dolomitization takes place more rapidly while the solutions are descending or ascending no definite answer can be given without experimental work. It is believed that the process probably occurs throughout the journey of the underground water, as explained on pages 636–639. Doubtless in many cases where there is local dolomitization adjacent to the main underground circulation channels, the process has taken place while the waters were ascending, for, as shown on page 583, the trunk channels of underground waters are more often ascending than descending. Excellent illustrations of local dolomitization by ascending waters are those already referred to at Glenwood Springs, Colo., described by Spurr,[a] and in the Carboniferous limestones of Missouri, adjacent to the lead and zinc areas described by Bain.[b] But in many cases of dolomitization along joints and other fractures the water was doubtless descending. The process may have been accomplished by waters which were ascending at one time and descending at another time. For instance, when the rock was somewhat deeply buried, a channel may have been occupied by ascending waters, and when brought nearer to the surface by erosion this same channel may have been occupied by descending waters, and dolomitization continued throughout the process.

Various regions could be mentioned which illustrate the above-mentioned conditions for dolomitization. One of the best of these is that portion of the limestones of the Mississippi Valley which is in the belt of cementation. It is well known that these limestones have been broken at various times so as to produce joint fractures and local faults, and thus furnish channels for ready circulation. In the belt of weathering the great Cambro-Silurian limestone, which contains magnesium, and the magnesium of the other rocks is continuously being dissolved and carried downward

[a] Spurr, J. E., Geology of the Aspen mining district, Colorado: Mon. U. S. Geol. Survey, vol. 31, 1898, pp. 212–216.

[b] Bain, H. F., Van Hise, C. R., and Adams, G. I., Preliminary report on the lead and zinc deposits of the Ozark region: Twenty-second Ann. Rept. U. S. Geol. Survey, pt. 2, 1901, pp. 208–210.

into the openings of the belt of cementation. After a given period of deformation the process of dolomitization continues until the openings are closed and circulation is checked, to begin again as soon as new openings are formed by earth movements. The process goes on with intermittent speed until a state of equilibrium is approximately reached between the calcium-magnesium solutions and the adjacent rock.

Other excellent illustrations of areas in which the conditions are favorable for dolomitization are furnished by various districts in the Cordilleras. Here in many areas recent orogenic movements and intrusion and extrusion of magma have taken place. The movements open new cracks and crevices in the limestones. The volcanic rocks, intruded or extruded, raise the temperature of the rocks and promote the activity of the solutions. Furthermore, the increase in temperature promotes the process of carbonation in the belt of weathering. In areas where there are limestones, recent volcanism, and orogenic movement, the conditions are especially favorable for the transfer of magnesium from the belt of weathering to the belt of cementation, with resultant dolomitization.

MARBLE.

In describing the processes of recrystallization and dolomitization in limestones, marbles have been accounted for in the main. Marble is the term which is applied to evenly granular, finely or coarsely interlocking calcite, dolomite, or intermediate minerals. (Pl. IV, *C*.) In the process of recrystallization it is common for a change to take place in the color of the rocks, as a result of which marbles are ordinarily white or pinkish white, rather than blue or gray, although marbles may, of course, have various other colors.

As already mentioned, marble results mainly from limestone in consequence of recrystallization or dolomitization, or the two combined. The absolutely conclusive evidence on this point is the increase of size of the mineral particles in marbles as compared with limestones. (See Pl. VI, *A* and *B*.) The formation of one mineral particle of marble of average size required a multitude of particles of the limestones, probably thousands; and in those cases where the grains of marble are coarse and the original limestone was fine perhaps many thousands were required. There is no mechanical process which alone can merge a great number of mineral

particles into a single mineral. This can be done only by solution and deposition, or recrystallization. It is notable in this connection, as explained below, that in proportion as the rocks were deep seated and as orogenic movements were severe the marbles are likely to be coarse grained, and were therefore thoroughly recrystallized. If the deformation were mechanical, the greater the severity of the movement the greater would be the strain effects mentioned below.

The development of marble is frequently assisted by the intrusion of igneous rocks. If the masses be large they may furnish the conditions of heat necessary for the solutions to be able to recrystallize the limestone for a considerable distance about the intrusive. Of course, in many regions orographic movements and volcanism are synchronous, and in such cases the conditions furnished by the movements and those furnished by the intrusive combined are particularly favorable to the process of recrystallization. Recrystallization may have been completed in regions of comparatively little disturbance, and thus occasionally in unfolded regions calcareous rocks are locally found to which the term marble is applicable. But the great belts of marble occur in regions in which orographic movements have taken place, and especially in rocks which have been so deeply buried as to be in the zone of anamorphism. This is shown by the association of the marbles with slates, schists, and gneisses—rocks which have been metamorphosed in the lower zone. Where the forces and agents were sufficiently potent to recrystallize the more refractory minerals, the recrystallization of the calcite and dolomite is probable, even if the marbles do not give such clear evidence of the fact as does slate, schist, or gneiss. Calcite and dolomite are most ready to respond to stresses by solution and deposition, and therefore to recrystallize, and also mechanically by development of twinning structures, by movement along gliding and cleavage planes, and by granulation.[a] (See Pl. VI, *C* and *D*.) Indeed, they are the most mobile of all the minerals which make up large masses of rocks. The minerals, halite, niter, etc., are even more mobile, but their rock masses are relatively small.

In consequence of the great mobility of calcite and dolomite, marbles generally differ in structure from the associated metamorphosed slaty,

[a] See Adams, F. D., and Nicolson, J T., An experimental investigation into the flow of marble: Philos. Trans. Royal Soc., London, ser. A, vol. 195, 1901, pp. 363–401.

schistose, or gneissose rocks, in that they are massive and evenly granular, although the mineral particles commonly show other strain effects mentioned below. The explanation of the general lack of slaty and schistose structures is believed to lie largely in the fact that the process of recrystallization under favorable conditions goes on almost pari passu with the deformation, and thus at any given moment the minerals lack but little of adjustment to their environment. In so far as the calcite and dolomite are left with residual strain there is a tendency to recrystallize. Their mobility is such that this tendency often prevails, and the minerals are largely released from strain. But in many instances release from strain is not perfect, for when thin sections are examined in many of the apparently completely crystalline marbles strain effects remain. Cataclastic structures occur in variable amounts; strain shadows are usual; twinning bands are very abundant, often are exceedingly fine, and frequently the lamellæ are curved, in such instances showing conclusively the existence of residual strain effects. And it is not always true that during the development of marble the process of crystallization so nearly keeps pace with movement as to prevent the formation of a secondary structure. In such cases the marbles may have a well-developed cleavage. This is well illustrated in some of the pre-Cambrian cleavable marbles of the Laurentian Mountains, by the cleavable Cambro-Silurian marbles of western Massachusetts, described by Dale,[a] and in the marbles of Alabama at Talladega Mountain. (See fig. 22 and Pl. V, *A*.) At this latter locality the marble cleaves as evenly and smoothly as a slate. Where marbles have a cleavage it is found to conform to the cleavage of the surrounding rock. The cleavage is found to be wholly due to a dimensional arrangement of the mineral particles. (See Chapter VIII, p. 760.) The fact that the cleavage of the mineral particles has nothing to do with the cleavage of the rock is explained by the rhombohedral cleavage of calcite resulting in fracture with equal ease in three directions. In this respect calcite and dolomite contrast strongly with the minerals

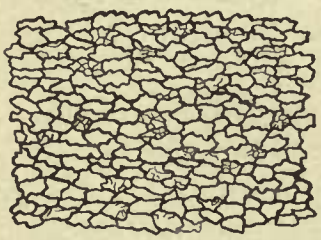
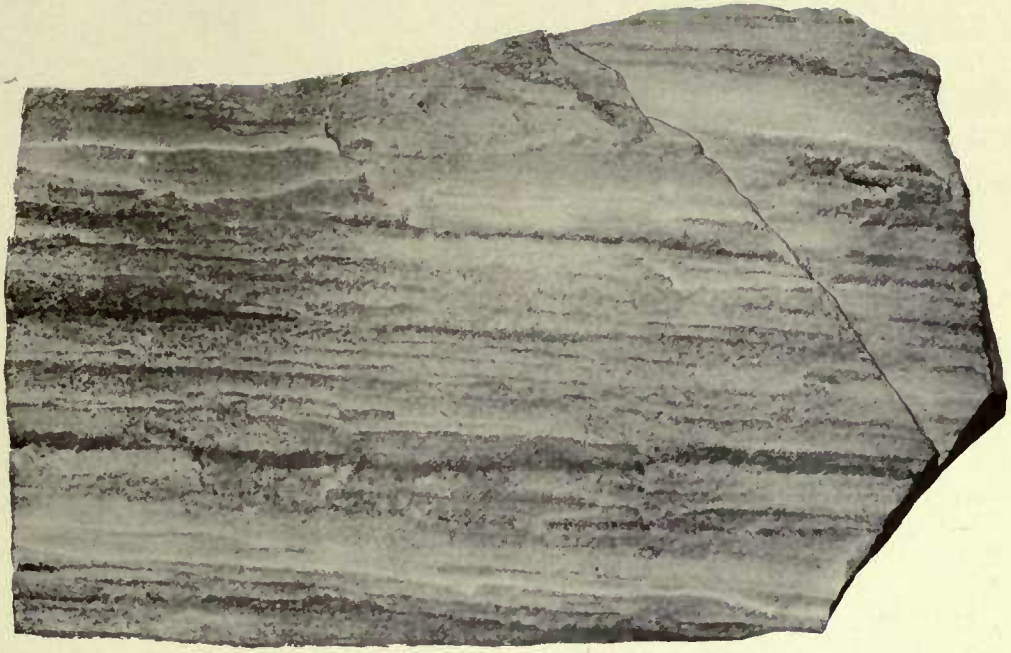


FIG. 22.—Sketch of oval irregular grains of calcite with longer diameters parallel. From schistose marble, Talladega Mountain, Alabama. After Leith.

[a] Pumpelly, Raphael, Wolff, J. E., and Dale, T. Nelson, Geology of the Green Mountains in Massachusetts: Mon. U. S. Geol. Survey, vol. 23, 1894, pp. 181–182.



A

B

TEXTURES OF METAMORPHOSED MARBLES.

A. Schistose marble from Talladega Mountain, Alabama. *B*. Tremolitic marble from Canaan, Conn. After Hobbs.

such as mica, the cleavage of which often controls the cleavage of rocks. The rare existence of cleavable marbles in connection with marble formations, the larger parts of which lack cleavage, as in the case of the marbles of the Appalachian regions just mentioned, seems to be conclusive evidence that the granular character of ordinary marbles is due mainly to the processes of ready solution and deposition, or recrystallization, as above explained.

Adams and Nicolson have experimentally deformed Carrara marble.[a] Among the various reasons for selecting this marble was its evenly granular character and absence of strain effects. The deformation was accomplished under the conditions of pressure of the zone of anamorphism. Cylinders of marble confined on their sides by strong steel bands were shortened by pressure, and under these circumstances the shape of the marble was changed without perceptible cracks being produced. The process was carried on under various conditions.

First, the dry marble was deformed at ordinary temperatures. The rock thus deformed was found to be weaker than the original rock, but sufficiently strong to show that the particles were partially welded. The thin sections of the marble showed a cataclastic structure "identical with that seen in the feldspars and many gneisses."[b] Many of the grains were flattened, and these grains showed strain shadows and fibrous structures due to minute polysynthetic twinning.

Second, the dry marble was very slowly deformed during a period of about four months at a temperature of 300° C. The deformed marble was found to be strong, but not quite so strong as the original rock, showing a nearer approach to perfect welding than in the case of the marble deformed at ordinary temperatures. The thin sections showed a tendency toward rock cleavage. "Cataclastic structure is absent, but almost every grain shows an exceedingly fine fibrous structure. When examined under a high power this fibrous structure resolves itself into an extremely narrow polysynthetic twinning—the whole grain consisting of slightly sinuous twin lamellæ, extinguishing in alternate sets. Each individual is usually twinned throughout, the lamellæ passing from end to end, although a single lamella often varies somewhat in width from place to place. The

[a] Adams, F. D. and Nicolson, J. T., An experimental investigation into the flow of marbles: Philos. Trans. Royal Soc. London, ser. A, vol. 195, 1901, pp. 363–401.

[b] Adams and Nicolson, cit., p. 375.

calcite grains, which in the original rock are practically equidimensional, are now often distinctly flattened, some of them being three or even four times as long as they are wide. Some grains can be seen to have been bent around others adjacent to them, the twin lamellæ and the extinction curving with the twisted grain. In other twisted individuals the twin lamellæ only extend in to a certain distance from the margin of the grain, leaving a clear untwinned portion in the center; and other crystals again show not only the fibrous structure due to twinning in one direction, but broader lamellæ crossing this obliquely. As the twinning in all cases is probably parallel to—$\frac{1}{2}$R—, this is due to the appearance of a set of twin lines parallel to a second face of the rhombohedron."[a] . . . . . "There has been no breaking—the rock has not been crushed in the ordinary sense of the term. The movement has been brought about partly by twinning, but chiefly by a deformation of the grains due to a slipping on their gliding planes."[b] (Pl. VI, *C.*)

Third, the dry marble was deformed during eight and one-fourth hours—much more rapidly than in the second case—at a temperature of 400° C. The result in this case was very similar to that in the previous case. From this experiment it was concluded that "quick deformation at a high temperature shows therefore that calcite has freer movement in its gliding planes at a high temperature and breaks less readily than when cold."[c] (Pl. VI, *D.*)

Fourth, the marble was slowly deformed during a period of fifty-four days, at a temperature of 300° C., in the presence of water gas. This rock after deformation "is not weaker, but actually stronger, than the original rock."[d] The thin sections of the rock showed substantially the same textures and structures as in the case of the dry marbles deformed at 300° or 400° C. The "granulated material is so trivial in amount that the deformation may be said to be due exclusively to movements on the gliding planes of the calcite, accompanied by polysynthetic twinning. It is thus identical in character with that seen in the case of the marble when deformed while dry, either at 300° C. or 400° C." . . . . . "There are no signs of solution and redeposition of calcium carbonate, even in this iron-stained portion of the rock. The presence of water, therefore, did not influence the character of the deformation. It is just possible, however,

[a] Adams and Nicolson, cit., p. 379. [b] Op. cit., p. 380. [c] Op. cit., p. 382. [d] Op. cit., p. 385.

PLATE VI

calcite grains, which in the original rock are practically equidimensional, are now often distinctly flattened, some of them being three or even four times as long as they are wide. Some grains can be seen to have been bent around others adjacent to them, the twin lamellæ and the extinction curving with the twisted grain. In other twisted individuals the twin lamellæ only extend in to a certain distance from the margin of the grain, leaving a clear untwinned portion in the center; and other crystals again show not only the fibrous structure due to twinning in one direction, but broader lamellæ crossing this obliquely. As the twinning in all cases is probably parallel to—$\frac{1}{2}$R—, this is due to the appearance of a set of twin lines parallel to a second face of the rhombohedron."[a] . . . . . "There has been no breaking—the rock has not been crushed in the ordinary sense of the term. The movement has been brought about partly by twinning, but chiefly by a deformation of the grains due to a slipping on their gliding planes."[b] (Pl. VI, *C.*)

Third, the dry marble was deformed during eight and one-fourth hours—much more rapidly than in the second case—at a temperature of 400° C. The result in this case was very similar to that in the previous case. From this experiment it was concluded that "quick deformation at a high temperature shows therefore that calcite has freer movement in its gliding planes at a high temperature and breaks less readily than when cold."[c] (Pl. VI, *D.*)

Fourth, the marble was slowly deformed during a period of fifty-four days, at a temperature of 300° C., in the presence of water gas. This rock after deformation "is not weaker, but actually stronger, than the original rock."[d] The thin sections of the rock showed substantially the same textures and structures as in the case of the dry marbles deformed at 300° or 400° C. The "granulated material is so trivial in amount that the deformation may be said to be due exclusively to movements on the gliding planes of the calcite, accompanied by polysynthetic twinning. It is thus identical in character with that seen in the case of the marble when deformed while dry, either at 300° C. or 400° C." . . . . . "There are no signs of solution and redeposition of calcium carbonate, even in this iron-stained portion of the rock. The presence of water, therefore, did not influence the character of the deformation. It is just possible, however,

[a] Adams and Nicolson, cit., p. 379. [b] Op. cit., p. 380. [c] Op. cit., p. 382. [d] Op. cit., p. 385.

PLATE VI

PLATE VI.

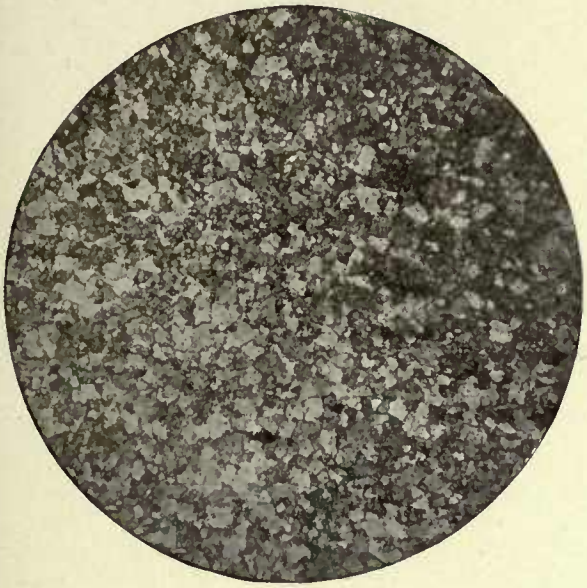
PHOTOMICROGRAPHS OF LIMESTONE AND MARBLES.

A. Limestone from Wauwatosa, Wis., showing the evenly granular character of a compact limestone. After Buckley.

B. Marble from Cockeysville, Md. After Diller.

C. Carrara marble after having been slowly deformed during 124 days at a temperature of 300° C. The calcite has yielded by gliding. After Adams.

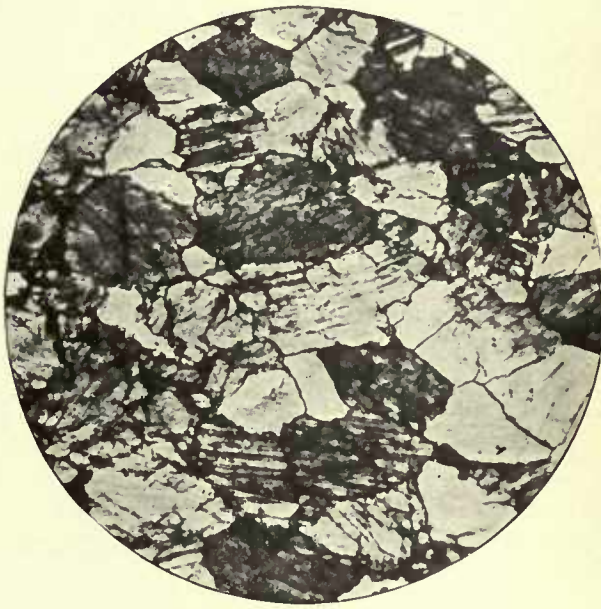
D. Carrara marble deformed at 400° C. The slide shows a uniform mosaic of somewhat flattened grains free from all fracturing or cataclastic structure. After Adams.



A

B

C



D

PHOTOMICROGRAPHS OF LIMESTONE AND MARBLES.

that there may have been a deposition of infinitesimal amounts of calcium carbonate along very minute cracks or fissures, thus contributing to maintain the strength of the rock. No signs of such deposition, however, are visible."[a]

It has been pointed out in another place (see pp. 747–748) that the greater strength of this sample, as compared with those in which water was not present, is almost conclusive proof that solution and deposition, or recrystallization, did take place to some extent.

Adams and Nicolson compare the structures produced in the Carrara marble artificially deformed with limestones and marbles in various regions where the rocks have been metamorphosed under deep-seated conditions. In 21 rocks from different regions, 10 of which are marble and 11 of which are limestones, they find all the structures which they have artificially produced to be paralleled.[b] But an equal number of rocks from other regions, only 3 of which are limestones, 2 dolomites, and 16 marbles,[c] which, as shown by the greater number of marbles, have undergone more profound metamorphism, they say "do not present any undoubted evidence of movement under pressure. Their structure is that of a mosaic, apparently resulting in each case from the recrystallization of a previously existing finer-grained limestone. This process, as described by Lepsius in the Attic marbles,[d] consists of the enlargement or growth of certain of the constituent grains at the expense of others until finally a coarse-grained mosaic is produced."[e] In these instances it is apparent that recrystallization is the dominant process, for only by this process can large individuals be produced by the merging of small ones. (See Chapter VIII, pp. 690–696.) Adams and Nicolson conclude: "While, therefore, recrystallization undoubtedly plays an important, and in many cases probably a chief part, in the great movements which are observed to have taken place in the limestones of contorted districts, this process is by no means the only one by which such movements are brought about. Many limestones under pressure in the earth's crust *flow* precisely as metals do, by deformation of the com-

[a] Adams and Nicolson, cit., p. 385.

[b] Op. cit., pp. 387–390.

[c] Op. cit., pp. 389–390; Nos. 22–42.

[d] Lepsius, R., Geologie von Attika; ein Beitrage zur Lehre vom Metamorphismus der Gesteine, Dietrich Riemer, Berlin, 1896, p. 186.

[e] Adams and Nicolson, cit., p. 397.

pressed grains, and without the intervention of water or any other solvent."[a] If this last sentence were written with the word *may* before "*flow*," no exception to the conclusion would be taken. While the process of flattening by movement along gliding planes undoubtedly occurs in marbles, it by no means follows, even in the 21 rocks in which the residual strain effects are described, that this was the chief process in their metamorphism. Indeed, in the production of the marbles from the original limestones, in order that the rocks could change from the very fine-grained condition of limestone to that of marble, recrystallization must have occurred, as explained on pages 808–809. Therefore to explain the metamorphism of the 21 rocks showing residual strain effects, we must place recrystallization as the chief process. During or after this, mechanical deformation supplemented recrystallization and gave the various strain effects described. Indeed, the history of these 21 rocks is very nearly analogous to the complete history of the Carrara marble experimentally deformed by Adams and Nicolson. Nature, in producing the Carrara marble free from strain effects, utilized recrystallization as the chief process. Later Adams supplemented this process by mechanical deformation. This later artificial deformation was an unimportant episode as compared with the recrystallization by nature.

Therefore, while I have no doubt that during the deformation of marble all the mechanical movements which Adams and Nicolson have described occurred, I hold that these, in the case of the production of marble from limestone, are entirely subordinate to, although they assist, the dominant process of solution and deposition, or recrystallization. And if this be true for marbles it can not be doubted that for those rocks composed of minerals which are less mobile than calcite and dolomite, and which do not have ready gliding planes in various directions, recrystallization was the process of paramount importance. It is certainly yet to be proved that, in such rocks as the slates, schists, and gneisses, movement along gliding planes is a process of consequence in their metamorphism.

CHERTY LIMESTONES, CHERTY DOLOMITES, AND CHERTY MARBLES.

Chert is a term used to include all forms of finely crystalline nonfragmental silica, including opaline, semicrystalline, and completely crystalline varieties. It differs from quartzite and novaculite in being nonfragmental.

[a] Adams and Nicolson, cit., p. 398.

It is well known that in many limestones, dolomites, and marbles are nodules and belts of opal, semicrystalline opal, chalcedony, finely crystalline quartz, or coarsely crystalline quartz, or various combinations of these materials. Such rocks are called cherty limestones, cherty dolomites, and cherty marbles. The siliceous material may constitute separate nodules. The nodules may unite at their ends so as to form layers of varying thickness within the limestone. The chert may be in bands with no evidence of a nodular character. Bands of chert usually have a lenticular form. The lateral extent of the lenses is likely to be in direct proportion to their thickness. The layers, which are a few centimeters in thickness, are usually only a few meters in lateral extent. The less numerous layers, which are several meters in thickness, may have a lateral extent of a number of kilometers. At the horizon at which one lens dies out others may appear, and thus the large lenticular bands at a definite horizon be analogous in their relations to magnified nodules. Rarely the masses of chert are many meters thick and many kilometers in length, constituting considerable formations. So far as such formations occur, they are treated on a subsequent page. The limestone or marble formations containing nodules or thin layers or bands of chert as subordinate members, and usually having no great lateral extent, are known as cherty limestones or cherty marbles.

The majority of those who have worked on chert in the cherty limestones, including Wallich, Sorby, Sollas, and Hinde, regard the silica of the chert as having been deposited by organisms simultaneously with the limestone. Of these organisms siliceous sponges appear to be the most important, although radiolaria and diatoms are of much consequence. All these animals live under essentially the same conditions as the limestone-building animals. On the whole, in proportion as rocks are old, the evidence of the organic origin of the silica becomes less and less. Oftentimes in the Paleozoic and pre-Paleozoic cherty limestones no remnants of sponge, diatom, or radiolarian can be found. But this does not show that organisms were not as important in these formations as in the later formations, since there has been a longer time for their obliteration through recrystallization. On the whole, I incline to the belief that the silica of the cherty limestones and marbles is mainly due to organic precipitation, although this source is supplemented by contributions furnished by ground waters, as explained below.

The question now arises why the chert occurs so generally segregated in nodules, thin layers, and bands in the limestone. The silica as deposited by organisms is in the amorphous, and therefore readily soluble, form. It has been explained on pages 120–123 that during the rearrangement of minerals by solution and deposition there is a marked tendency for those of the same kind to segregate, and this tendency is strong in proportion as the minerals are readily soluble. At a point where there is more than an average amount of silica, especially large grains of quartz, this silica draws to it silica from the surrounding rocks through the solutions, under the principle expounded on pages 74–76, that large masses and grains grow at the expense of smaller ones. In this principle we have the explanation not only of the segregation, but of the lenticular character which is so characteristic of the masses. The principle under which larger masses or grains grow at the expense of smaller ones is that the change tends to give the total mass the smallest surface area. This would be ideally accomplished by the spherical form of the masses; but since openings are numerous and circulation is comparatively easy along the beds, the lenticular masses, especially those which are more than a few centimeters in diameter, have a greater lateral than vertical extent. But in proportion as the chert masses are small they are likely to approach the spherical form, and this gives proof of the correctness of the principle. It is therefore believed that the segregation and form of nodules and thin lenticular layers of chert in limestones are adequately explained by concentration through solution and deposition.

Where, however, there are bands of chert of considerable thickness, so as to constitute definite members of a formation, and especially where there are formations of chert, the above explanation is not adequate. It is probable that many such deposits were originally dominantly siliceous. The principle of the natural groupings of animals of like kind into a colony is well known. Where there was a colony of silica-secreting organisms a major band or formation of silica would form. Modern deposits composed of nearly pure silica formed by siliceous organisms show how lenticular bands of chert may have originated. For instance, the well-known diatom deposit of chert used as tripoli at Richmond, Va., is about 10 meters thick.[a] Such deposits may have been enlarged by segregations

[a] Merrill, George P., The nonmetallic minerals of the U. S. National Museum: Rept. Smithsonian Inst. for 1899, Washington, 1901, p. 219.

from the surrounding limestone, for in regions in which there are local colonies of silica-secreting organisms there are sure to be similar organisms among the limestone-secreting organisms.

Therefore I hold that the nodules and minor bands of chert in the limestones are mainly due to segregations by solution and deposition, but that many of the larger and more persistent bands of chert are at places where the silica was originally deposited in large part by the siliceous organisms, although the silica of such bands has usually been rearranged. Both original and secondary masses of chert may occur in the same formation. For instance, in the lead and zinc district of southwestern Missouri, in the Carboniferous limestone are one or more large and continuous bands of chert which can be mapped as separate members of a formation, and these are believed to be chiefly original. But in this limestone are innumerable minute bands and lentils, from a fraction of a centimeter to several centimeters in thickness, and extending from a few centimeters to a few meters, to which the colonization theory can not be fully applied, and which were doubtless largely segregated as above described. Bands of intermediate width are doubtless due in varying degrees to original deposition and to secondary segregation. Where limestone containing chert reaches the surface, it is well known that the amount of the cherty material in the belt of weathering is relatively great This is largely due to the more ready solubility of the limestone than of the chert, in consequence of which the percentage of chert is increased. At or near the surface the removal of the limestone may be almost or quite complete, and thus produce a partly coherent or even incoherent belt of almost pure chert along the surface. In many cherty limestone regions, where the soil is residual, one might think that nearly the entire rock was chert, so prominent does this material appear in the soil and in the rock near the surface.

The silica originally present in a given mass of limestone in consequence of organic precipitation is not the only source of silica for nodules and bands of chert. The silica of the limestone in the belt of cementation may be greatly increased. This may be done in two ways. First, where the limestones reach the surface, and the segregation above mentioned takes place in the belt of weathering, a part of this silica is being continuously dissolved and transported downward into the belt of cementation This process is especially active where the silica has not become wholly

crystallized. Second, limestones in the belt of cementation may receive important additions of silica even where they do not reach the surface but are overlain by other rocks. It has been explained that the process of carbonation of the silicates liberates colloidal silicic acid. This is taken into solution, and passes downward into the belt of cementation. The material transported to this belt, either from another part of the limestone or from the silicates, is selectively precipitated as explained on pages 634–636, the limestone being simultaneously dissolved, and thus silicification takes place.

This process of segregation of silica, both within the belt of weathering of the limestones and in the belt of cementation, is steadily cumulative. Therefore it is possible for limestones which originally were not especially siliceous to contain considerable amounts of silica. However, it is supposed that usually those limestones which are heavily siliceous contained originally a considerable quantity of silica as an organic precipitate.

SILICATED MARBLES.

The silicated marbles are products intermediate between marbles and the silicate rocks. The processes by which they are formed are a combination of those producing marble and those resulting in silication of the carbonates. These processes will not be described in detail here, since they are given under the immediately preceding and succeeding headings. The conditions for their formation are intermediate between those ruling in the production of evenly granular pure marble and those ruling in the complete replacement of the carbon dioxide by silica.

Like the marbles and the silicate rocks, the silicated marbles form in the zone of anamorphism, and especially in connection with mechanical action or igneous intrusion. The most abundant silicate minerals of the marbles are pyroxene and amphibole, but many other silicates may form. Of these, olivine, chondrodite, vesuvianite, tourmaline, and mica are the most important. In any given case one or two silicates may be the preponderant ones, and under such circumstances a more definite name may be given to an individual rock or formation. For instance, if tremolite is the dominant silicate it may be called a tremolitic marble (Pl. V, *B*); if diopside is the dominant silicate it may be called a diopsidic marble. If two silicates occur together, as, for instance, diopside and olivine, the rock

may be called a diopsidic and olivinitic marble. In a similar manner, other appropriate names may be given to individual formations, more accurately defining their character than the general term silicated marbles.

Of the two most prevalent groups of minerals, pyroxene and amphibole, calcium is more abundant in the former. Therefore from the nearly pure calcium carbonate rocks the pyroxenes are likely to develop, rather than the amphiboles. Thus from the rocks which have not been strongly dolomitized wollastonite and diopside form, rather than tremolite, because the latter mineral requires a larger proportion of magnesium. Where the rocks have been dolomitized before silication the amphibole tremolite is especially likely to develop.

In the calcareous rocks in which there is a considerable amount of fragmental material mingled, and consequently aluminum is plentiful, the aluminous pyroxenes and amphiboles are likely to form.

In so far as the process of silication takes place by the combination of solid silica with the carbonate, and the liberated carbon dioxide escapes, the volume of the rock is decreased. The decrease in volume varies from a very small percentage to very considerable amounts as they approach the silicated rocks, which have a decrease in volume varying from 20 to 40 per cent.

The silicated marbles grade into the pure marbles on the one hand and into the silicate rocks on the other. The term silicated marble is properly applied to rocks which range from those in which the silicate minerals are unimportant to those in which the carbonates are subordinate. Those rocks in which the silicates are not abundant should be classified with the marbles, and those in which the carbonates are not abundant should be classified with the silicate rocks. Thus limited, the silicated marbles occur at very numerous localities among the rocks profoundly metamorphosed under deep-seated conditions. This state of affairs naturally exists to a greater extent among the old than among the new formations, and therefore this class of rocks is especially abundant among the Paleozoic and pre-Paleozoic sedimentary rocks. Illustrative localities of the silicated marbles occur in almost every country. The best representatives in this country are found in the pre-Cambrian formations of Lake Superior and Canada and in the Paleozoic formations of the Appalachian region.

SILICATE ROCKS.

In certain localities the limestones and dolomites may be wholly replaced by silicates. Of these silicates the most important are the pyroxenes and amphiboles. Of the pyroxenes the most common are wollastonite, diopside, and sahlite. Of the amphiboles the most important are tremolite and actinolite. Of course other pyroxenes and amphiboles may be present, such as the augites and hornblende. Other silicates which rather frequently replace limestones are olivine, mica (including muscovite, biotite, and phlogopite), chondrodite, vesuvianite, and tourmaline. In fact, almost any of the dense silicates may develop. The limestones are transformed to silicate rocks only in the zone of anamorphism. The silicates are the ultimate products of alteration under the conditions there obtaining. The process is one of simple silication; the silica originally present in the limestone, or contributed to it by ground waters, replaces the carbon dioxide and forms the silicate.

If the rock be pure limestone, wollastonite forms, according to the following reaction:

$$CaCO_3+SiO_2+nH_2O=CaSiO_3+CO_2+nH_2O,$$

with a decrease in volume of 31 per cent, provided the silica is a solid and the carbon dioxide escapes.

If the rock be magnesian, diopside or tremolite forms, according to the following reactions, respectively:

$$CaMg(CO_3)_2+2SiO_2=CaMgSi_2O_6+2CO_2,$$
$$3CaMg(CO_3)_2+4SiO_2=CaMg_3Si_4O_{12}+2CaCO_3+4CO_2,$$

with a decrease in volume of 40.11 and 25.20 per cent, respectively, provided the silica is a solid, the calcium carbonate remains as a solid when tremolite forms, and the liberated carbon dioxide escapes.

If the limestone be one which contains many bases in important amounts, other more complex silicates develop, with variable decreases in volume; and thus we have the explanation of subordinate amounts of augite, hornblende, mica, chondrodite, vesuvianite, tourmaline, etc., which are so common as replacement products of marble.

The localities in which the calcium-carbonate formations have been completely changed to silicate formations are comparatively few, and at

such localities the formations are usually not extensive. These deposits are well illustrated by the kalk-silikat-hornfelse of the Harz Mountains, described by Lossen and Rosenbusch.[a]

GENERAL STATEMENTS.

The processes of crystallization, dolomitization, silicification, and silication of the limestones and the resultant rocks have been separately described as if each occurred alone. As a matter of fact, in the field all the processes may occur together in various proportions, and hence we may have all gradations between limestone and dolomite, between limestone and marble, between pure limestones, dolomites, and marbles and siliceous limestones, dolomites, and marbles, and between these rocks and those in which the process of silicification is complete. Finally, we may have all gradations between the various forms above mentioned and those in which the silicates have developed in subordinate, important, or dominant amounts. Therefore, within the limestone series there are complete gradations between the various rocks of the series.

IRON-BEARING CARBONATE FAMILY AND METAMORPHOSED EQUIVALENTS.

The iron-bearing carbonate family and metamorphosed equivalents comprise siderite, ankerite, and parankerite; ferruginous shales, ferruginous cherts, and jaspilites; actinolitic and grüneritic marbles; and actinolitic quartz rocks and grüneritic quartz rocks.

SIDERITE, ANKERITE, AND PARANKERITE.

The original forms of the iron-bearing carbonates include siderite, ankerite, parankerite, and gradations between them. (Pl. VII, *A*.) With these carbonates, as with the less ferriferous carbonates, chert is an almost universal associate. It varies in amount from a minute quantity to an important amount, and occasionally to dominance. The alterations of the above carbonate compounds as minerals have been considered on pages 242–245. As rock masses they may be considered under the terms siderite and ferrodolomite, including under the latter term all gradations between siderite on the one hand and dolomite on the other.

The iron-bearing carbonates occur mainly in layers in the stratified rocks, and are therefore of sedimentary origin.

---

[a] Rosenbusch, H., Physiographie der Mineralien, Stuttgart, 1896, vol. 2, p. 97.

The bedded iron-bearing carbonates vary from nearly pure carbonate material through siliceous and clayey iron-bearing carbonates to carbonaceous, siliceous, and argillaceous rocks. The most widespread of the iron-bearing carbonates are of Carboniferous age. Other extensive deposits of iron-bearing carbonates are those of Algonkian age in the Lake Superior region. A subordinate amount of the iron-bearing carbonates occurs as veins, but so far as this is true the material will not be here considered.

ORIGIN OF SIDERITE, ANKERITE, AND PARANKERITE.

So far as siderite, ankerite, and parankerite are composed of calcium, magnesium, and carbonic acid, the sources of the materials are the same as for the same materials in the calcium-magnesium carbonate family just considered. But we must account for the iron. As the iron-bearing carbonates are aqueous sedimentary rocks, the iron must have been deposited from water. The formations containing iron carbonate plentifully are generally local. Often they are associated with carbonaceous rocks. Many of them are closely associated with the coals which are known to have formed in lagoons and estuaries, some of which possibly were only imperfectly connected with the sea. Deposits from which coal is derived are formed at times of very luxuriant vegetation near the level of the sea, where the soil is very moist. It is believed that the physiographic conditions for the deposition of iron-carbonate deposits are similar to those which obtain in flat-lying areas near water level, where vegetation is very luxuriant. It may be recalled that under such conditions carbonation of the silicates goes on very rapidly. (See Chapter VI, pp. 476–477.) The iron silicates are decomposed precisely as are the others. It has been fully explained on pages 470–471 that where vegetation is very abundant, in very humid areas, the oxygen of the soil is not sufficient for the oxidation of the vegetation. It was seen that under such conditions ferric oxide oxidizes some of the residual vegetation, and is thereby reduced to the ferrous oxide. The oxidation of the organic compounds produced abundant carbon dioxide. The ferrous oxide originally present and that formed by reduction unites with the carbon dioxide and produces iron carbonate.

Where soluble ferrous compounds are formed abundantly, as above described, it is probable that the rocks which are being destroyed in the

belt of weathering are rather rich in iron; for instance, intermediate or basic igneous rocks. If rock of this favorable composition were scoriaceous volcanic rocks, the conditions would be exceptionally favorable to the production of such salts by the process of carbonation of the silicates, the partial reduction of the ferric iron, and its union with carbonic or sulphuric acids.

Such conditions are illustrated by the Lake Superior region, where the iron for the iron-bearing formations was largely derived from basic volcanic rocks. In that region in each of the important iron-bearing districts below the iron-bearing series are found greenstones, often ellipsoidal, in many places porous and amygdaloidal, in many places schistose, all rich in iron. Below the Mesabi, Penokee, Marquette, and Menominee series are great masses of basic volcanic rocks. In the Penokee and Crystal Falls districts basic volcanic outflows were contemporaneous with or immediately preceded the deposition of the iron-bearing formation. In the Vermilion district of Minnesota and in various districts of Canada, including the Michipicoten district, the iron-bearing formations immediately overlie enormous masses of ellipsoidal and often amygdaloidal basic volcanic formations.

The ground waters take iron compounds abundantly into solution wherever the rocks are of a composition and texture favorable to furnishing iron. The waters take a longer or shorter journey before issuing at the surface. The issuing waters, aside from the iron compounds, contain, among other abundant compounds, the calcium and magnesium carbonates. Where extensive iron-carbonate deposits have formed, it is probable that the sources of supply were adjacent to shallow standing bodies of water, such as arms of seas, lagoons, estuaries, etc. Under such circumstances the ground waters usually issue at the lower places a short distance above or below the level of the water. As has been explained, such bodies of water are generally rich in vegetation. In these bodies the iron salts are precipitated.

As to the form in which the iron salts enter the seas, we can judge only by analogy, but if the present be a guide to the past, the iron was chiefly as a carbonate and to a subordinate extent as a sulphate, although it might have been in part in the form of other salts. When the iron salts reach the lagoon, they are precipitated under favorable conditions as ferric hydrate or

possibly in part as basic ferric sulphate. Supposing the iron salt to be carbonate, it would be precipitated according to the following reaction:

$$4FeCO_3+3H_2O+2O=2Fe_2O_3.3H_2O+4CO_2.$$

Where this process goes on, on an extensive scale, limonite bodies (considered on pages 842–843) are built up.

It was formerly supposed that this reaction took place as a result of the work of oxygen and moisture alone, and this is true to some extent. But recent observation has shown that where in lagoons iron carbonate is abundant the oxidation is largely performed through the agency of a class of bacteria called the iron bacteria. It has been found that these bacteria are unable to exist without the presence of iron carbonate or manganese carbonate, but the iron carbonate is the chief compound used. This material they absorb into their cells. There the iron carbonate is oxidized and the limonite is precipitated. Says Lafar:

> The decomposing power of these organisms is very great, the amount of ferrous oxide oxidized by the cells being a high multiple of their own weight. This high chemical energy on the one hand, and the inexacting demands in the shape of food on the other, secure to these bacteria an important part in the economy of Nature; the enormous deposits of ferruginous ochre and bog iron ore, and probably certain manganese ores as well, being the result of the activity of the iron bacteria.[a]

Evidence is furnished of the precipitation of the limonite of bog iron-ore deposits in this manner by the discovery in some of them of large numbers of the sheaths of the iron bacteria.[b] Further evidence of the importance and activity of these bacteria is furnished by their partly or completely closing water pipes of cities where the water contains a considerable amount of iron carbonate.[c]

The iron part of the salts carried down to the sea as a sulphate would be likely to be thrown down as basic ferric sulphate,[d] according to the following reaction:

$$12FeSO_4+6O+(x+9)H_2O=Fe_2(SO_4)_3.5Fe_2O_3.xH_2O+9H_2SO_4.$$

---

[a] Lafar, F., Technical mycology, Lippincott & Co., 1898, vol. 1, p. 361.

[b] Fischer, A., The structure and functions of bacteria, trans. by A. Coppen Jones, Clarendon Press, Oxford, 1900, p. 69.

[c] Lafar, cit., p. 361.

[d] Pickering, S. P. U., On the constitution of molecular compounds; the molecular weight of basic ferric sulphate: Jour. Chem. Soc. London, vol. 43, 1883, p. 182.

The material thrown down as a hydrated ferric oxide and basic ferric sulphate is mingled with more or less of organic material, and a deposit of considerable thickness may thus be built up. This deposit is below the level of ground water, and is therefore in the zone of incomplete oxidation, or is under the conditions of the belt of cementation. The oxygen required for the partial oxidation of the organic material is derived in part from the ferric oxide, and the iron is reduced to the ferrous form; but probably this reaction does not take place on an important scale at the surface. The reducing agent may be regarded as carbon, carbon monoxide, or some of the carburetted hydrogens, such as methane. The result is the same in any case. The oxygen and the carbon produce carbon dioxide, and thus the conditions are reproduced for the production of iron carbonate. A representative reaction may have been as follows:

$$2Fe_2O_3.3H_2O+3CO_2+C=4FeCO_3+3H_2O.$$

In the Mesabi district of Minnesota Leith has shown that a compound, which he has called greenalite, exists on an extensive scale as an important original mineral of the iron-bearing formation.[a] (Pl. VII, *B*.) The exact composition of greenalite has not yet been determined, but according to Clarke it appears to be either

$$Fe'''_2Fe''_3(SiO_4)_3.3H_2O \text{ or else } FeSiO_3.nH_2O,$$

with the probability somewhat in favor of the latter composition.[b] Where silica in a colloidal form is especially abundant, with limonite produced as explained above, and with organic matter to serve as a reducing agent, the silica may unite with the ferrous oxide produced by the reduction of the ferric oxide to ferrous oxide through the organic matter, and thus with hydration produce hydrous ferrous silicate. The formation of the hydrous silicate under such circumstances, rather than the carbonate, may have been dependent upon the law of mass action.

The principles are illustrated by the conditions under which the oxidized compounds of zinc occur in the Wisconsin and southwestern Missouri districts. In the Wisconsin district silica is not especially abundant, and where zinc sulphide is oxidized the zinc oxide unites with carbon dioxide

[a] Leith, C. K., The Mesabi iron-bearing district of Minnesota: Mon. U. S. Geol. Survey, vol. 43, 1903, pp. 100–168.

[b] Leith, cit., p. 246.

and forms smithsonite ($ZnCO_3$). But in Missouri silica, partly in the amorphous form, is very abundant; and there, when the zinc sulphide is oxidized, the oxide of zinc largely unites with the silica, forming calamine [$(ZnOH)_2SiO_3$]. Both smithsonite and calamine occur in both districts, but calamine occurs abundantly only where silica is abundant. Similarly, where in lagoons the iron is reduced to the ferrous form, it would unite with the silica on a large scale, provided that compound were abundantly present in a form suitable for union. Hence the hydrated ferrous silicate of the Mesabi district is regarded as a product of the chemical reactions of the zone of katamorphism.

Another iron compound, besides ferrous silicate, which is associated with iron-bearing carbonates is iron sulphide. It is believed that this compound results from the reduction of the basic ferric sulphate. It has been pointed out that, so far as the iron goes into lagoons as a sulphate, it is thrown down as basic ferric sulphate [$Fe_2(SO_4)_3.5Fe_2O_3.xH_2O$]. This compound in the belt of cementation in the presence of organic matter which strongly demands oxygen is reduced, the oxygen being abstracted from the sulphur, and so far as possible from the iron, thus producing bisulphide of iron. The excess of ferrous iron unites with the carbon dioxide, or exceptionally in part with the silica, forming ferrous carbonate or ferrous silicate. Supposing ferrous carbonate were formed, and the reducing agent to be CO, the reaction may be written:

$$2[Fe_2(SO_4)_3.5Fe_2O_3.xH_2O]+33CO=3FeS_2+21FeCO_3+12CO_2+2xH_2O.$$

In an analogous manner the reaction may be written for ferrous silicate as follows:

$$2[Fe_2(SO_4)_3.5Fe_2O_3.xH_2O]+33CO+21SiO_2=3FeS_2+21FeSiO_3+33CO_2+2xH_2O.$$

So far as there is water in the silica or the ferrous silicate, this may be added to both sides of the equation. The reducing agent may be supposed to be C or H or some combination of the two. This would modify the equation, but would not change the principle involved.

Perhaps the formation of the compounds, ferrous silicate and bisulphide of iron, can not logically come under the caption "iron-bearing carbonates;" but since they occur with the iron-bearing carbonates as subordinate constituents, and only in a few districts in sufficient masses to be regarded as independent formations, they are here considered.

It is concluded from the foregoing that the main sources of the iron-bearing carbonates are the iron-bearing silicates of various rocks, and especially intermediate and basic igneous rocks which are porous. From these, iron carbonate and other soluble iron salts are produced by the reactions of the belt of weathering. They are transported to inclosed or partly inclosed bodies of standing water by the underground solutions. The material is there thrown down, mainly as ferric hydrate. By the action of the organic matter upon the ferric iron it is reduced to ferrous oxide and unites with the carbon dioxide simultaneously produced, or with silicic acid, forming iron carbonate or iron silicate. So far as the iron is a sulphate it is reduced wholly or in part to sulphide.

In what manner the calcium and magnesium are thrown down with the iron is uncertain. In the inclosed lagoons, which must have been of exceptional character, as shown by the precipitation of the iron itself, it is possible that calcium and magnesium might so accumulate as to be precipitated chemically, and thus the carbonate be originally an iron-bearing calcium-magnesium carbonate, in which the iron varies from a subordinate to a dominant constituent. This suggestion is the more plausible because where iron is abundantly precipitated as hydroxide and remains in that form life is usually somewhat sparse. While this may be a partial explanation of the precipitation of the calcium and magnesium, the calcium may have been mainly thrown down through the instrumentality of life, in the same manner as were the ordinary limestones, and the substitution of magnesium for calcium may have occurred subsequently, precisely as in the case of the limestones, thus forming the ferrodolomite.

FERRUGINOUS SHALES, FERRUGINOUS CHERTS, AND JASPILITES.

In the zone of katamorphism ferruginous shales or ferruginous cherts are produced from the iron-bearing carbonates, and by modifications of these in the zone of anamorphism jaspilites are formed. By ferruginous shales are meant rocks which have a bedded structure and are composed mainly of oxide of iron, but which include a greater or less quantity of finely disseminated quartz. By ferruginous cherts are meant those rocks which consist of two sets of bands, one of which is composed mainly of iron oxide and the other mainly of chert.

FERRUGINOUS SHALES.

The ferruginous shales are produced from siliceous siderite, ankerite, or parankerite, by the decomposition of the iron carbonate and the partial or complete oxidation and hydration of the ferrous oxide, combined with the rearrangement of the particles, and frequently the introduction of silica. In the zone of katamorphism the first alteration is the oxidation and partial or complete hydration of the ferrous oxide, with the liberation of carbon dioxide, thus producing limonitic and hematitic slate and various gradations between them. The reaction for hematite is as follows:

$$2FeCO_3+O=Fe_2O_3+2CO_2.$$

For limonite it is:

$$4FeCO_3+3H_2O+2O=2Fe_2O_3.3H_2O+4CO_2.$$

Where the constituents of the rock are not extensively rearranged the original regular stratiform arrangement of the siderite is preserved, and the rock is called a ferruginous shale. Where the iron oxide is mainly hematite the rock may properly be called hematitic shale; where mainly limonite, a limonitic shale; and where both are abundant, hematitic and limonitic shale. Simultaneously with the oxidation of the iron carbonate, calcium and magnesium carbonate, so far as they are present, may be partially or completely dissolved.

FERRUGINOUS CHERTS.

At the same time the iron carbonate is altered the silica, which is usually present in greater or less quantity, may become concentrated in layers by exactly the same process as it becomes concentrated in layers in limestones. and thus there may be produced a hematitic and limonitic chert. The rock may be somewhat regularly banded, or the bands may be very irregular and broken. As the rearrangement goes further, oxide of iron is apt to become concentrated in bands, alternating with bands which are predominantly chert. Also in this stage a concretionary nodular or geodal character is apt to be developed, and then the material may be called banded iron oxide and chert, or chert with bands and shots of iron oxide. (Pl. VII, *C.*) In the earlier stages frequently the silica, as in the original rock, is partly opaline, and as the rearrangement becomes more nearly complete the silica takes the form of finely crystalline, interlocking

quartz. Each grain may become coated with a film of hematite, thus giving it a red color. Some of the more irregularly banded rocks have been called cherts with bands and shots of ore. In these rocks minute openings exist between the particles, and minor geodal cavities are very common, thus giving the rock a porous character. This porosity results in part from the diminution in volume in the change from iron carbonate to hematite or limonite. Also it is partially caused by the solution of the calcium and magnesium carbonates and silica more rapidly than iron oxide is substituted for these materials. During the process the dissolved iron carbonate may be transported a greater or less distance. In openings precipitation may take place, and thus veins of hematite or limonite be produced. Under favorable conditions, which are more fully discussed in Chapter XII, on "Ore deposits," the excess of silica and other material may be dissolved and nearly pure hematite or limonite bodies be formed. Thus from the iron carbonate large iron-ore deposits are produced. The details of the process of transformation I have fully discussed elsewhere.[a]

In closing this part of the subject it may be noted that to the stage where the ferruginous shales and ferruginous cherts are produced the iron has been twice in the form of the carbonate, or once as a carbonate and once as a silicate, and twice in the form of an iron oxide, and, therefore, that at least four chemical transformations have occurred to that time. These were: (1) When the material was first taken into solution as carbonate, (2) when it was precipitated in the sea as hydroxide, (3) when it was transformed to an iron carbonate or hydrous iron silicate, and (4) when by the underground waters it was again chemically changed to limonite or hematite.

JASPILITES.

The jaspilites are banded rocks, the bands being composed of hematite and chert in various proportions. The jaspilites differ from the ferruginous cherts in that the siliceous bands have a bright-red color, due to the fact that each granule of quartz is coated with and includes innumerable minute flakes of blood-red hematite. The bands in which the iron oxide is predominant are composed chiefly of specular hematite.

---

[a] Irving, R. D., and Van Hise, C. R., The Penokee iron-bearing series of Michigan and Wisconsin: Mon. U. S. Geol. Survey, vol. 19, 1892, pp. 268–295. Van Hise, C. R., The iron-ore deposits of the Lake Superior region: Twenty-first Ann. Rept. U. S. Geol. Survey, pt. 3, 1901, pp. 326–328.

The hematitic and limonitic shales produced in the zone of katamorphism, and especially in the belt of weathering, are so unlike the original rocks from which they were derived that one would not be inclined to believe that they were derived from ferriferous carbonates if the actual transitions had not been traced at many localities.[a]

After the ferruginous shales and ferruginous cherts have developed they may undergo still further alterations. For instance, the hematitic and limonitic shales may, after having been formed, become deeply buried, and thus pass into the zone of anamorphism. In this position they are in the zone of dehydration, and this process will occur, especially if mass-mechanical action takes place. Thus there are produced the banded hematitic siliceous rocks known as jaspilites, which are merely banded hematite and quartz rocks. In some of the bands the quartz is dominant, in others the hematite is dominant, and in still others both are abundant. In the quartz bands innumerable minute grains of quartz are stained by still more numerous microscopic flakes of red oxide of iron. The iron oxide bands usually include much quartz. In proportion as mass-mechanical action is severe the rocks take on a strongly developed schistose structure, due to the similar dimensional arrangement of the hematite flakes. From the nearly pure iron-oxide bands, bands of hematite-schist are produced, the hematite being in brilliant parallel flakes resembling flakes of mica. These bands of hematite are similar to the solid specular ore bodies.

Excellent illustrations of hematitic schists and jaspilites are furnished by the upper horizon of the Lower Huronian of the Lake Superior region, especially in the Marquette district. In this district, after the original iron carbonate had formed, the upper part of the formation was subjected to alteration in the belt of weathering on an extensive scale, and thus was transformed to hematitic and limonitic shales. It was afterwards buried under the great mass of deposits of the Upper Huronian, and thus passed into the zone of anamorphism. Later with that series the ferruginous

[a] Irving, R. D., and Van Hise, C. R., The Penokee iron-bearing series of Michigan and Wisconsin: Mon. U. S. Geol. Survey, vol. 19, 1892, pp. 193, 201–202, 205, 253, 294. Clements, J. Morgan, and Smyth, H. L., with W. S. Bayley and C. R. Van Hise, The Crystal Falls iron-bearing district of Michigan: Mon. U. S. Geol. Survey, vol. 36, 1899, p. 62. Van Hise, C. R., with Bayley, W. S., and Smyth, H. L., The Marquette iron-bearing district of Michigan: Mon. U. S. Geol. Survey, vol. 28, 1897, pp. 336–375. Bayley, W. S., The Menominee iron-bearing district of Michigan: Mon. U. S. Geol. Survey, vol. 46, 1904, pp. 397, 466–468.

shales were subjected to profound mass-mechanical action and then were transformed to jaspilites. Simultaneously with the process of jaspilitization of the upper part of the iron-bearing formation the basal conglomerate of the Upper Marquette series, largely composed of the weathered material of the iron-bearing formation, was transformed to a jasper-conglomerate. It has been noted that the formation of the ferruginous shales and ferruginous cherts required four chemical transformations. Where jaspilites occur a fifth chemical change has taken place—dehydration.

ACTINOLITIC AND GRÜNERITIC MARBLES.

In the zone of anamorphism the alterations of the iron-bearing carbonates are entirely different in character from those in the zone of katamorphism. In the lower zone the iron carbonates go through a set of transformations which are analogous to those of limestones under similar conditions. Furthermore, magnetite forms. Therefore the rocks which are first produced are actinolitic or grüneritic magnetitic marbles. In these rocks the chief constituents are dolomite, magnetite, and actinolite or grünerite, often also quartz.

The development of the dolomite is the same as in the marbles. By the silication of the carbonate either actinolite or grünerite is produced, with diminution of volume—the former in case the bases present are calcium, magnesium, and iron, and the latter in case the carbonate was originally siderite or the original rock was greenalite (hydrous silicate of iron). Where some iron sulphide or oxygen is available a part of the ferrous iron may change to magnetite; and rarely a very little hematite may form. Very frequently there is greater or less rearrangement and concentration of the silica, so that bands or nodules of this material are formed. If the metamorphism takes place under mass-static conditions, there is little tendency for parallel orientation of the actinolite and grünerite. In proportion as the alteration occurs under mass-mechanical conditions there is a tendency for parallel orientation of the developing amphibole. Since actinolite-magnetite rocks or grünerite-magnetite rocks, the end products of the alteration of the siderites, ferrodolomites, and greenalite rocks are much more common than the intermediate rocks treated under this heading, the reactions producing the silicates are more fully discussed under the next heading.

ACTINOLITE-MAGNETITE-QUARTZ ROCKS AND GRÜNERITE-MAGNETITE-QUARTZ ROCKS.

The actinolite-magnetite-quartz rocks consist of interlocking actinolite, magnetite, and quartz, with or without other iron oxides, and accessories of various kinds. (Pl. VII, *D.*) The grünerite-magnetite-quartz rocks consist of interlocking grünerite, magnetite, and quartz, with or without other iron oxides, and accessories of various kinds. In a given case the magnetite or actinolite or grünerite may drop out, or nearly so. Where the magnetite becomes subordinate the rocks are actinolite-quartz rocks and grünerite-quartz rocks; where the actinolite or grünerite drops out the rocks become magnetite-quartz rocks.

The conditions under which these rocks form are those of the zone of anamorphism. In many cases the actinolite and grünerite have a random or radial fibrous arrangement to their bands, but in other cases they are arranged with their longer axes in a common direction, with a marked tendency toward crystallographic orientation. Where the parallel arrangement of the amphibole occurs the quartz and magnetite also have a tendency to have their longer dimensions in the same direction as that of the actinolite and magnetite. Where this arrangement is marked—and this is very common—the term gneiss is properly applicable to the rocks; and thus we may have actinolite-quartz-gneiss, magnetite-quartz-gneiss, etc. The amount of parallel arrangement of the particles is a measure of the amount of orogenic movement during the process of recrystallization. Where there is little tendency to parallelism the rocks were probably crystallized by metasomatism under mass-static conditions. Where the arrangement is well developed the recrystallization occurred during powerful orogenic movement.

This relation is well illustrated by the Marquette district of Michigan. In the central part of the district the folding is only moderately close, and there the parallel arrangement of the mineral particles is very imperfect. At the west end of the district the folding is of the closest and most intense character, and there are beautiful coarse actinolitic and grüneritic gneisses, many of the mineral particles of which are arranged with almost perfect parallelism.

The most important change of the iron carbonate is to a silicate. Where the carbonate is nearly pure siderite, grünerite is produced, according to the following reaction:

$$FeCO_3+SiO_2=FeSiO_3+CO_2,$$

PLATE VII

PLATE VII.

PHOTOMICROGRAPHS OF IRON-BEARING ROCKS.

A. Sideritic rock from Penokee-Gogebic district of Michigan and Wisconsin.

B. Greenalite or ferrous silicate rock from Mesabi district of Minnesota. After Leith.

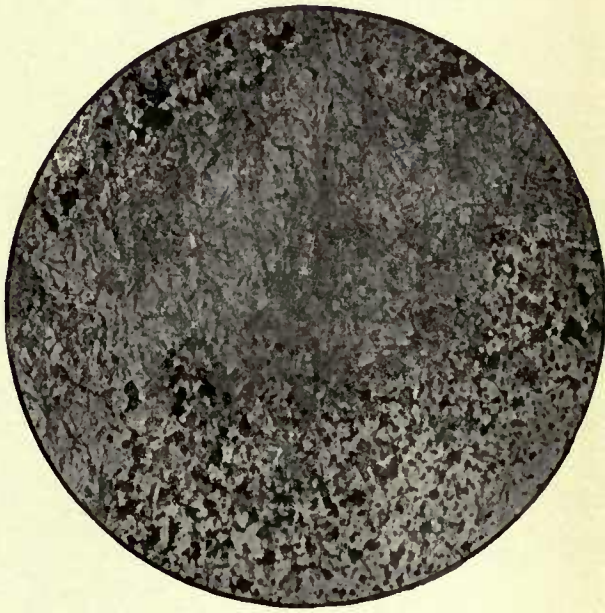
C. Concretionary chert resulting from the alteration of iron carbonate. From Penokee-Gogebic district of Michigan and Wisconsin.

D. Actinolite-magnetite-quartz rock resulting from the alteration of iron carbonate. From Penokee-Gogebic district of Michigan and Wisconsin.

A

B

C



D

PHOTOMICROGRAPHS OF IRON-BEARING ROCKS.

with a decrease of volume of 32 per cent, provided the silica be a solid and the carbon dioxide escape. Where the original material was hydrous ferrous silicate, greenalite, simple dehydration only is necessary to form the grünerite.

Where the iron-bearing carbonate bears calcium and magnesium in considerable quantity, instead of grünerite being produced sahlite or actinolite may be formed. Supposing the carbonate to be normal ankerite, sahlite is produced, according to the following reaction:

$$CaFeC_2O_6.CaMgC_2O_6+4SiO_2=Ca_2MgFeSi_4O_{12}+4CO_2,$$

with a decrease in volume of 37 per cent, provided the silica be solid and the carbon dioxide escape.

From ankerite actinolite may be produced, according to the following reaction:

$$3(CaFeC_2O_6.CaMgC_2O_6)+8SiO_2=Ca_2Mg_3Fe_3Si_8O_{24}+8CO_2+4CaCO_3,$$

with a decrease in volume of 23 per cent, provided the silica be a solid, the $CaCO_3$ formed remain as a solid, and the carbon dioxide escape.

If a more ferriferous and less calcareous iron-bearing carbonate be taken, it would not be necessary to suppose any calcium carbonate to have separated.

The iron-bearing carbonates may be very impure, just as limestones may be impure; and in this case there may develop various other minerals. In proportion as impurities are mingled with the carbonates, other amphiboles and the pyroxenes, micas, garnets, and other heavy minerals such as olivine, may abundantly develop; and thus there may be produced a great variety of rocks, such as garnetiferous magnetite rocks, micaceous grünerite rocks, etc. As the impurities become abundant and the silicates other than grünerite, sahlite, and actinolite more prominent, the alterations become nearly those of the fragmental rocks, considered on page 853 et seq. Between the two there are of course all gradations.

But as a matter of fact, the two silicates which most extensively form by the alterations of the iron-bearing carbonates in the zone of anamorphism are actinolite and grünerite. Where these reactions are complete we may have, in place of the iron-bearing carbonate, actinolite rocks, grünerite rocks, and all gradations between them.

With the grünerite, actinolite, sahlite, or other silicates, magnetite usually develops to some extent, probably as follows:

$$2FeCO_3+FeS_2+2H_2O=Fe_3O_4+2H_2S+2CO_2.$$

The following reactions are also possible:

$$3FeCO_3=Fe_3O_4+CO+2CO_2;$$

or where there is sufficient oxygen:

$$3FeCO_3+O=Fe_3O_4+3CO_2.$$

The first reaction produces a decrease in volume of 47 per cent, and the second and third a decrease of 50 per cent, provided the hydrogen sulphide, oxygen, carbon monoxide, and carbon dioxide be ignored.

Observation in the field shows beyond question that the change from iron carbonate to magnetite takes place on an extensive scale. Which of the above reactions is the more important may be an open question. Since the change takes place in the zone of anamorphism, where the conditions are reducing instead of oxidizing, and since, as has already been explained (p. 828), pyrite is a very common associate of iron carbonate, I think it probable that the first of the three reactions written is the dominant one. The reactions of the second and third equations are identical with those which take place when iron carbonate is heated in a closed tube in the laboratory where oxygen is absent or deficient in amount. It is explained below that the development of magnetite from iron carbonate takes place on the most extensive scale where igneous rocks have been intruded. This suggests at first that the reactions may be those of dry heat, but this idea is probably not warranted, for the magnetite which forms from carbonate is usually segregated into crystals or clusters of crystals, and this leads me to believe that the change is accomplished through the agency of water, with heat as a promoting force and iron sulphide as one of the active agents.

In the group of rocks under consideration the relative proportions of the silicates, of magnetite, and of quartz are very variable. In some instances the actinolite or the grünerite is predominant, with quartz as a subordinate constituent, and we have a quartzose actinolite or quartzose grünerite rock. In other instances the predominant constituents are magnetite and quartz, and in still other cases quartz is subordinate in amount; hence we may have a magnetite-quartz rock, or a quartzose magnetite

rock. In still other instances all three classes of minerals are abundantly present, and we have actinolite-magnetite-quartz rocks or grünerite-magnetite-quartz rocks. Each of these different combinations of minerals may be of sufficient extent to constitute a member of a formation, or even an entire formation.

Which of the above rocks develops at a given place depends not only upon the original composition of the rocks, but upon the nature of the alteration. For instance, where in the original rock silica is subordinate and nearly pure siderite abundant, a quartzose-magnetite may develop, as at various places in the Lake Superior region. Where the conditions are such that the silicates form, the development of the actinolite or grünerite uses up both the iron carbonate and the silica, and an actinolite rock or a grünerite rock may be produced. Where silica was originally an abundant constituent both magnetite and the silicates are likely to develop. Thus we have various proportions of all the minerals, producing the magnetite-quartz rocks, the actinolite-magnetite-quartz rocks, the grünerite-magnetite-quartz rocks, the actinolite-quartz rocks and the grünerite-quartz rocks.

Usually a given formation, or member, does not show a perfectly homogeneous arrangement of the mineral particles. The original sedimentary rock is banded, and the different bands have different compositions. Naturally the transformation of these bands produces different combinations of minerals. Moreover, during the recrystallization there is a tendency, as explained in Chapter III (pp. 120–123), for minerals of the same kind to segregate. Hence, in any of the above cases, where as a whole a certain set of minerals are dominant within a rock, a single mineral, or two combined, may be largely segregated in bands; and in the alternate bands the other minerals be largely segregated. Thus a banded rock, consisting mainly of magnetite and quartz, may have a banded appearance as the result either of the segregation of the quartz and magnetite in separate bands or, more commonly, the segregation of more quartz and less magnetite in one band and less quartz and more magnetite in another band. In a similar manner alternate bands may be made up of actinolite or grünerite with quartz in various proportions, and of actinolite or grünerite with magnetite in various proportions. In still other instances the banding may be due to the combining of actinolite or grünerite, magnetite, and quartz in various proportions. In general, therefore, the alterations of the rock do

not destroy the original sedimentary banding, but, on the contrary, emphasize it. The striking banded appearance of actinolitic and grüneritic rocks is one of their most characteristic features.

The development of the actinolitic and grüneritic marbles and of the actinolitic, grüneritic, and magnetitic quartz-rocks is very greatly promoted by the presence of igneous rocks. Indeed, in the Lake Superior region, where iron silicates have been produced in large amounts from the iron-bearing carbonates and hydrous iron silicates over extensive areas, intrusive rocks, in large masses, seem to be invariably present. At the west end of the Penokee range in Wisconsin, and at the east end of the Mesabi district in Minnesota,[a] the entire iron-bearing formations have been changed to silicate-bearing rocks, and directly in contact with them—indeed, intrusive in them in a complex manner—are great batholithic masses of the basal gabbro of the Keweenawan. Also in the Mesabi district granite has been intruded in great quantities. In the Marquette district of Michigan, east of Negaunee, dolerite is a very abundant intrusive within the iron-bearing formation, and there in the iron-bearing formation the silicate rocks are again found, although not so abundantly as in the Mesabi and Penokee districts.[b] Not only do the great areas of the silicated rocks occur where there are great masses of intrusives, but intrusives are sure to be found where the silicated rocks appear locally abundant, as, for instance, adjacent to Humboldt, Mich., in the Marquette district. Apparently in the Lake Superior region the iron-bearing formations were not sufficiently deeply buried, or subjected to sufficiently strong orogenic movements to cause the silication of the carbonates to take place on an extensive scale for those reasons alone; but where these metamorphic conditions were reenforced and intensified by intrusive rocks, there the transformation took place. If any case of metamorphism ought to be called contact metamorphism, the development of the silicated rocks from the iron-bearing carbonates should

[a] Van Hise, C. R., and Irving, R. D., The Penokee iron-bearing series of Michigan and Wisconsin: Mon. U. S. Geol. Survey, vol. 19, 1892, pp. 257–260. Grant, U. S., Sketch of the geology of the eastern end of the Mesabi iron range in Minnesota: Eng. Year Book, Univ. of Minnesota, 1898, p. 58. Van Hise, C. R., and Leith, C. K., The iron-ore deposits of the Lake Superior region; section on the Mesabi district: Twenty-first Ann. Rept., U. S. Geol. Survey, pt. 3, 1901, pp. 359–360. Leith, C. K., The Mesabi iron-bearing district of Minnesota: Mon. U. S. Geol. Survey, vol. 43, 1903, pp. 159–164, 182–188.

[b] Van Hise, C. R., and Bayley, W. S., The Marquette iron-bearing district of Michigan: Mon. U. S. Geol. Survey, vol. 28, 1897, pp. 380–381.

be so designated, since in the Lake Superior region the presence of the igneous rocks seems to have been an essential condition for the process to take place on an extensive scale.

After the grüneritic or actinolitic rocks have developed in the zone of anamorphism, in consequence of denudation they may pass into the zone of katamorphism, or even into the belt of weathering. Then there will begin the processes of oxidation, hydration, and carbonation, as a result of which the magnetite is changed to hematite or limonite, and the actinolite and grünerite decompose into carbonate. However, since magnetite and the iron-bearing amphiboles are very refractory, this process is exceedingly slow, and usually has affected only comparatively thin layers of material adjacent to the surface or adjacent to openings in the rock. Indeed, the reagents of the belt of weathering and the upper part of the belt of cementation, which, as pointed out (pp. 830–831), may produce large iron-ore bodies where they have the original iron-bearing carbonates or the hydrous ferrous silicates to work upon, have nowhere in the Lake Superior region formed large ore bodies where they are working upon the grüneritic and actinolitic rocks. This follows directly from their refractory character, since the average amount of iron of the iron-bearing formation is essentially the same in both cases. In the refractory character of these rocks we have the explanation of the absence of rich workable iron-ore deposits for extensive areas in each of the iron-bearing districts of the Lake Superior region where the alterations of the original rocks in the zone of anamorphism developed actinolitic or grüneritic magnetite rocks.

GENERAL STATEMENTS.

From the foregoing pages it is apparent that the iron-bearing carbonates and the hydrous iron silicates are metamorphosed along two main lines, depending upon whether they are in the zone of katamorphism or the zone of anamorphism. Where they are altered in the zone of katamorphism, and especially in the belt of weathering, the ferruginous shales, ferruginous cherts, and ores result. Where they are altered in the zone of anamorphism the actinolitic and grüneritic marbles, or the actinolitic rocks and grüneritic rocks, are produced. Further, where the metamorphosed rocks produced from the iron-bearing carbonates and hydrous iron silicates change from one zone to another they are further

altered. The ferruginous shales and ferruginous cherts, products of the zone of katamorphism, when transferred to the zone of anamorphism are transformed to jaspilites. The actinolitic and grüneritic rocks transferred to the zone of katamorphism are altered to ferruginous shales and ferruginous cherts, but this change takes place so very slowly that these products have not been thus produced on a very large scale.

OXIDE ORDER.

IRON-OXIDE FAMILY.

The iron-oxide family comprises a number of oxides—anhydrous and hydrous. Of these limonite, hematite, and magnetite occur in sufficient masses to entitle them to consideration as rocks. Limonite is hydrated ferric oxide ($2Fe_2O_3.3H_2O$). Hematite is ferric oxide (Fe_2O_3). Magnetite is ferrosoferric oxide (Fe_3O_4). Many of the larger formations are intermediate between limonite and hematite. Some are partly hematite and partly magnetite. Usually subordinate minerals are associated with the iron oxides. Of these, quartz is almost universal. But all the carbonates, many of the hydroxides and silicates, and some of the sulphides are often associated. The carbonates and hydroxides other than of iron are apt to be associated with the limonites, and less commonly with the hematites. The silicates and sulphides are usually associated with the magnetites, and often with the specular hematites.

LIMONITE.

Limonite may compose considerable rock deposits. Ordinarily such deposits are not very thick, although they may have considerable extent. The deposits are commonly of very irregular thickness, or bunchy, being locally perhaps 3, 6, or 10 meters thick, and within a short distance almost disappearing.

Recent deposits of limonite are extensive. These occur in marshes and bogs. They have been worked to a greater or less extent as iron ores throughout the civilized world. Probably the most extensive deposits of limonite known are those of the Lower Silurian, which have been worked for ore in many countries.

The Silurian limonites and the limonites of many other horizons are largely replacement and concentration products of limestones, being therefore a result of metamorphism. In some districts the limestones originally

contained a small amount of iron carbonate. This carbonate has a history identical with that of the iron of the iron-bearing carbonates, discussed on pages 824–829. Locally the iron carbonate of the limestones has been picked up by the percolating waters. At various places these waters have been converged at localities favorably situated. At such localities the iron is precipitated from the carbonate according to the reaction:

$$4FeCO_3+2O+3H_2O=2Fe_2O_3.3H_2O+4CO_2.$$

Often simultaneously with this process calcium carbonate has been dissolved. Thus, at the surface of a limestone formation there may be produced a layer of limonite which passes downward into the limestone.

In still other cases the iron of limonites associated with limestones has been in large part derived from adjacent formations. In such cases the association is, in part at least, a consequence of the ready solution of the limestone, which makes it easy for the substitution to take place. Such substitution is likely to occur where underground waters from different sources unite, as, for instance, where the limestones are fractured, so as to be open and porous; where there are impervious basements, etc.

HEMATITE.

Hematite occurs in much larger masses than limonite. The hematite is not wholly anhydrous, but contains a variable amount of water. For instance, in the Mesabi hematite, the most extensive deposits of this oxide known, the combined water varies from 2.09 to 8.23 per cent.[a] Thus, there are all gradations between limonite and hematite, and the majority of the great soft iron-ore deposits contain limonite, hematite, the intermediate oxides, and various combinations of them. The more extensive iron-ore deposits of the United States, which are largely hematite, are those of the Algonkian and Archean of the Lake Superior region and the Clinton ore horizon of the Silurian. These masses of limonite and hematite were partly deposited in place as original sediments, but to a larger extent are due to subsequent segregations.

The limonitic hematites which occur as original sediments in place are identical in their development with the oxides of iron which are the original source of the iron carbonates. (See pp. 824–826.) In summary, iron salts,

[a] Leith, C. K., The Mesabi iron-bearing district of Minnesota: Mon. U. S. Geol. Survey, vol. 43, 1903, pp. 214–217.

as iron carbonate mainly, but subordinately iron sulphate and other compounds, are brought by underground solutions to shallow bodies of water, such as lagoons. By oxidation and hydration the material is thrown down as hydrated hematite or limonite, with a greater or less amount of basic ferric sulphate. But the larger masses of limonite and hematite are usually mainly produced by segregation subsequent to the formation of the original sediments. These, like the limonites, are largely replacement deposits of limestone or of some other carbonate rock. The Clinton hematite ore deposits are partly replacements of limestone which may have contained a small amount of iron carbonate, but according to various authors the hematites, as such, in large measure were deposited with the associated limestones. But the most extensive deposits of hematite known, those of the Lake Superior region, are segregations in formations which were originally in large measure iron-bearing carbonate or hydrous ferrous silicate. For these deposits the iron as carbonate has been transported to the places of deposition; there it meets other solutions bearing oxygen, and in consequence of the mingling of such solutions the iron is thrown down as a partially hydrated hematite, the reaction being:

$$2FeCO_3+O+nH_2O=Fe_2O_3+nH_2O+2CO_2.$$

It may be said, therefore, that limonitic hematite is either a direct chemical precipitate in the zone of katamorphism or is due to aqueous concentration in that zone.

Ordinarily, so long as limonite and limonitic hematite remain in the horizon in which they form, they are not further altered, since they are end products of metamorphism for the zone of katamorphism. But at or near the surface in arid regions, or in times of drought in humid regions, the more hydrous forms of the oxide may be dehydrated and thus pass into hematite.

The more important alterations of limonite and hydrated hematite take place when these ores pass into the zone of anamorphism. In that zone dehydration occurs. The limonites and more hydrated hematites are gradually decreased in amount, and where dehydration is complete hematite is formed. Where the change is from pure limonite to pure hematite a decrease in volume of 38 per cent is involved.

Where the rock is subjected to strong orogenic movements, not only does dehydration occur, but the iron becomes specular, and a laminated

texture is produced. Thus are formed the specular hematites. Where the movements are of extreme intensity the little flakelets of hematite may become flat and parallel, and thus resemble mica. Such a rock is a hematite-schist. Where more or less of a reducing agent is present at the time of the dehydration, magnetite may form and be associated with the hematite.

MAGNETITE.

Magnetite, with quartz and various silicates as subordinate constituents, may compose considerable rock bodies. Such material occurs as important members of the iron-bearing formations of the Lake Superior region, and in the gneisses of the eastern metamorphic region of the United States—in the Adirondacks, in the highlands of New York and New Jersey, and in the southern Appalachians, notably at Cranberry, N. C. But the greatest of the eastern magnetite deposits is that of Cornwall, Pa., in limestone of Lower Silurian age, underlain by Triassic intrusive trap. It is uncertain whether or not the gneisses with which many of these magnetitic rocks are associated are of sedimentary origin, but presumably many of them are. If these rocks be sedimentary it is more than probable that the magnetite members are also sedimentary. The most natural hypothesis as to the origin of these rocks is that they were iron-bearing carbonates metamorphosed as described on pages 834–841. The deep-seated metamorphism changed the original iron-bearing carbonates to magnetite, with the simultaneous development of quartz and silicates.

The production of magnetite from siderite may be supposed to be that of imperfect oxidation, the reaction being:

$$3\,FeCO_3 + O = Fe_3O_4 + 3CO_2.$$

But it has been seen (p. 828) that where iron carbonate is produced iron sulphide also is often found. Magnetite and pyrite, also, are often associated. In the deep-seated zone of anamorphism it can not be supposed that oxygen is usually present. It therefore appears to me that the more frequent reaction is that producing magnetite from siderite and pyrite. The change may be written thus:

$$2FeCO_3 + FeS_2 + 2H_2O = Fe_3O_4 + 2H_2S + 2CO_2.$$

These changes would result in a decrease of volume of 50.32 per cent for siderite to magnetite, or of 46.67 per cent for siderite and pyrite.

This diminution of volume furnishes an entirely adequate cause for the transformation.

Also magnetite may be produced under conditions of partial oxidation of iron sulphide, such as pyrite and pyrrhotite, according to the following reactions:

$$3FeS_2+4H_2O+4O=Fe_3O_4+4H_2S+2SO_2.$$
$$3Fe_{11}S_{12}+36H_2O+8O=11Fe_3O_4+36H_2S.$$

Le Conte describes the formation of magnetite by the imperfect oxidation of iron sulphide at Sulphur Bank, California.[a]

Some magnetites are undoubtedly formed by the alterations of limonite or hematite or intermediate compounds. The change of these oxides of iron into magnetite is likely to take place in the deep-seated zone where organic or other material is present which can take away the oxygen. At the same time dehydration occurs. The reaction may be written as follows:

$$3(Fe_2O_3).nH_2O-O=2Fe_3O_4+3nH_2O.$$

The oxygen abstracted unites with the carbon to form carbon dioxide, or with hydrogen to form water. Where the limonite or hematite is associated with iron sulphide it is not necessary that organic matter be present in order that the change shall take place; the sulphide may serve as the reducing agent. In this case the reaction may be written:

$$22(Fe_2O_3.nH_2O)+FeS_2+2H_2O=15Fe_3O_4+2H_2SO_4+22nH_2O.$$

Supposing the original oxide were hematite, the volume of the magnetite is 3.58 per cent less than that of the hematite and pyrite. So far as water was present dehydration took place and the percentage of decrease in volume is greater than given. Where the amount of the reducing agent is not sufficient to change all of the limonite or hydrated hematite to magnetite, dehydration only takes place for the remainder of the material, and consequently with the magnetite a variable amount of hematite is often associated. The segregation of iron oxide into rich deposits is further considered in Chapter XII, on "Ore deposits."

[a] Le Conte, Joseph, and Rising, W. B., The phenomena of metalliferous vein formation now in progress at Sulphur Bank, California: Am. Jour. Sci., 3d ser., vol. 24, 1882, p. 33.

SILICA FAMILY.

CHERT.

The silica deposits are all included under the general term chert. This term, as here applied to siliceous layers and formations, includes amorphous, partly amorphous, and crystallized silica. Often in the same mass may be seen very minutely spotted quartz grains separated by partly amorphous material, cryptocrystalline silica of various kinds, such as chalcedony, and completely crystalline quartz. In almost every extensive chert formation all these varieties are mingled in the most complex manner. Chert comprises both organic and chemical deposits.

The most extensive deposits of chert are those of organic origin, the silica being taken by certain animals and built into their hard parts, precisely as is calcium carbonate by other animals. The animals which absorb the greatest amount of silica are sponges of a certain class. Other than the sponges, radiolaria and diatoms appear to be the more important. These and other animals may build up considerable deposits of chert. As illustrations of chert formations of organic origin may be mentioned the Cretaceous flints described by Wallich,[a] the flints of the Trimmingham chalks described by Sollas,[b] and extensive deposits of chert in Ireland, England, Wales, Spitzbergen, and Axels Island, described by Hinde.[c] Hinde says that the chert beds in Yorkshire have an estimated thickness of about 30 meters, and in North Wales of 100 meters, and these, he says, can be proved to be due to sponge remains.[d]

But probably the most extensive formation of chert which is known to be of organic origin is that of Axels Island, where the beds of cherty material, according to Hinde, aggregate 260 meters in thickness.[e] This is not a continuous mass of chert, but consists of a number of beds interstratified with limestone.

---

[a] Wallich, G. C., A contribution to the physical history of the Cretaceous flints: Quart. Jour. Geol. Soc. London, vol. 36, 1880, pp. 68–91.

[b] Annals Mag. Nat. Hist., 5th ser., vol. 6, 1860, p. 438. See also Walcott, C. D., Fossil medusæ: Mon. U. S. Geol. Survey, vol. 30, 1898, p. 18.

[c] Hinde, G. J., On the organic origin of the chert in the Carboniferous limestone series of Ireland, and its similarity to that in the corresponding strata in North Wales and Yorkshire: Geol. Mag., London, new ser., dec. 3, vol. 4, 1887, pp. 435, 436. Hinde, G. J., On the chert and siliceous schists of the Permo-Carboniferous strata of Spitzbergen, and on the character of the sponges therefrom, which have been described by Dr. E. von Dunikowski: Ibid., vol. 5, pp. 241–251.

[d] Hinde, cit., vol. 4, pp. 435–446.

[e] Hinde, cit., vol. 5, p. 243.

The source of the silica for organisms is probably in part that dissolved in sea water. Since, however, when filtered the pure sea water contains only one part in 250,000, Murray and Renard "consider the probability of the pelagic organisms which secrete silica obtaining it from the hydrated silicate of alumina or clay held in suspension as well as the silica held in solution. This might explain the fact that these organisms abound in brackish waters, and waters of low salinity and low temperature, where the clay is more abundant than in the warmest and saltest waters of the ocean. In the case of siliceous sponges, which are rooted for the most part in the oozes and clays, Messrs. Murray and Renard think that the silica of their skeletons may be derived from the silica in solution in sea water, or from the colloid silica set free during the decomposition of the feldspathic rock fragments and minerals in the deposits."[a]

Chemical deposits of silica may be formed when underground solutions, especially hot solutions, reach the surface. The silica, in consequence of the decrease in pressure and temperature, is precipitated. Such deposits are known as siliceous sinter. The best known examples are the geyserite formations of the Yellowstone Park.

The silica for chemical deposits is believed to be mainly derived from that contributed to the underground waters by the process of carbonation in the zone of katamorphism, and especially in the belt of weathering, as fully explained in Chapter VI (pp. 475–480). But it is certain that a portion of the silica of the underground waters is directly derived by solution of amorphous and semicrystalline silica of organic deposits and by the solution of quartz itself. It is frequently supposed that crystallized quartz is not dissolved by the ground waters, but, as shown by Hayes,[b] quartz crystals at the surface are dissolved and corroded, and observations in many mines show that the solutions have dissolved quartz in large quantities from the wall rocks. This is illustrated by the granite of the Portland mine, at Cripple Creek, Colo., where the quartz and mica are dissolved and the feldspar is comparatively untouched. While, therefore, silica for chemical precipitation is derived directly from the solution of quartz, a vastly greater amount is the colloidal silicic acid liberated by the process of

[a] Walcott, C. D., Fossil medusæ: Mon. U. S. Geol. Survey, vol. 30, 1898, p. 20.

[b] Hayes, C. W., Solution of silica under atmospheric conditions: Bull. Geol. Soc. America, vol. 8, 1897, pp. 213–220.

carbonation of the silicates and that furnished by the solution of amorphous and semicrystalline quartz.

Rearrangement of chert.—Chert, as deposited by organisms or chemically, may be hydrous and amorphous, semicrystalline, or completely crystalline. In proportion as it is amorphous or semicrystalline, it is likely to be easily and extensively dissolved and rearranged. Usually the opaline, semicrystalline, and completely crystalline materials, are mingled in an intricate manner. Very often a single thin section shows all varieties of material. In many sections the opaline or amorphous silica constitutes a background in which there are innumerable polarizing spots of chalcedony and quartz. The process of rearrangement may go on until the material, whether of organic or chemical origin, becomes wholly crystalline quartz.

If crystallization be complete, there may be produced a finely crystalline rock composed of closely fitting, minute particles of quartz, many of them with crystal outlines, which average only a small fraction of a millimeter in diameter. Such rocks may be called finely crystalline quartz rocks. Representatives of them are the whetstones of Arkansas and the quartz rock of the Penokee district of Wisconsin. In many cases such rocks are stained by oxide of iron, and these are often called jasper.

The crystallization may go further, so as to produce coarsely crystalline quartz rock. This process of crystallization of the amorphous material so as to produce first, chert; next, finely crystalline quartz; and next, coarsely crystalline quartz, occurs under the laws of physical chemistry. In so far as the silica passes from a hydrous to an anhydrous condition the volume is lessened. In so far as it passes from an amorphous to a crystalline condition the volume is lessened. The change in volume in the passage of one of the ordinary opals to quartz has been calculated on page 221 to be 22.81 per cent. All these processes may occur at any depth, precisely the same as the process of dolomitization. But they are promoted by depth of burying and by high temperature, and therefore the finely crystalline and coarsely crystalline quartz rocks derived from organic silica or siliceous sinter have usually been buried to a very considerable depth.

If in addition to depth of burying there be profound orogenic movement, the rock may be further recrystallized and mechanically sliced, and

thus the quartz particles be so rearranged that their maximum and mean diameters are in a common plane, producing quartz-schist.

It has already been explained (pp. 818–819) that where silica is rearranged it is sure to be segregated, because any area of chert attracts materials of like kind to itself, and large masses grow at the expense of small ones. Even in the cases where the cherts are undoubted replacements the source of the silica may largely have been sponge spicules, diatoms, etc., which were disseminated through the limestones. This material can not be discriminated from that furnished by the ground waters coming from some other formation. The essential fact is that such a deposit is a replacement deposit, whether the silica be derived from the decomposition of silicate, by the solution of sponge spicules, or in some other manner.

In order that the silica may be concentrated, it is of course necessary that the material previously occupying the place shall be dissolved. Such concentration and solution are especially likely to occur in those formations which originally contained a considerable amount of cherty material, and which were readily soluble. The best representatives of rocks of this class are the carbonates—calcareous, magnesian, and ferruginous. At the time the chert is segregated the carbonate is dissolved. It therefore follows that in the calcium-magnesium carbonate family and the iron-bearing carbonate family the most extensive deposits of chert should be expected; and with this the facts correspond.

Observation shows that many carbonate formations have been extensively silicified. Positive evidence of the replacement of carbonates by chert is furnished by formations which contain numerous silicified fossils which were originally calcareous, such as the mollusks and corals. Where fossils of this kind, now chert, are contained in a mass of chert, it is natural to suppose that the formation was in the main originally calcareous. A good illustration of extensive replacement of calcareous formation by silica is that of the Tampa Bay chalcedony pseudomorphous after coral.

Where replacement has been extensive, the average compositions of considerable masses of rocks have been greatly changed—indeed, where pure limestone is replaced by chert, entirely changed. There is no means by which one can estimate the amount of silica that has been introduced from an outside source in the silicification of great carbonate formations. Doubtless the amount of such material is great, but probably in most

instances the process of silicification of the carbonate formations is largely that of segregation of the originally dispersed silica of the limestone formations themselves.

No better illustrations of extensive cherts are known to me than those furnished by the iron-bearing formations of the Lake Superior region. Here silica in its various forms and iron oxide constitute almost the entire weathered belt of the cherty iron-carbonate formations. Locally in this region the chert is segregated almost entirely free from iron oxide. Such occurrences are illustrated by the chert near Amasa, in the Crystal Falls district of Michigan.[a] Within the limestones extensive chert beds are also found at many localities. Some of the best known in this country are those of the Boone chert formation, of Lower Carboniferous age, in the lower Mississippi Valley, and the thick bed of chert in the Carboniferous limestone of southwestern Missouri.[b]

In none of these formations are organic remains found from which the chert is derived. Where the rearrangement has gone so far that the siliceous organisms, if they once existed, would have been destroyed, it becomes difficult or impossible to certainly discriminate between chert deposits which are mainly organic and those which are mainly chemical. It is natural to suppose that where chert beds are somewhat persistent they are largely organic, although doubtless they may have been extensively rearranged and have had great additions of silica. On the other hand, where the chert masses are small, nodular, and bunchy, and especially where they are exceedingly irregular, it may be supposed that they are mainly substitution products. But reasoning along either of these lines is of very doubtful value.

For instance, the rather persistent nature of the chert formations above mentioned in the Lake Superior region might be taken as evidence that they were mainly organic deposits in their present position. However, a close study of this district leads to the conclusion that these formations by substitution for carbonate now occupy the place of cherty iron-bearing carbonates and silicates, and that they are mainly explained by segregation

[a] Clements, J. Morgan, and Smyth, H. L., with Bayley, W. S., and Van Hise, C. R., The Crystal Falls iron-bearing district of Michigan: Mon. U. S. Geol. Survey, vol. 36, 1899, pp. 62, 177.

[b] Bain, H. F., Van Hise, C. R., and Adams, Geo. I., Preliminary report on the lead and zinc deposits of the Ozark region: Twenty-second Ann. Rept. U. S. Geol. Survey, pt. 2, 1901, pp. 86–87, 129.

from the parts of the formation once above the plane of denudation. The cherty formations of the Lake Superior region are usually steeply inclined, and therefore descending water rapidly and easily segregates silica on a large scale from material widely disseminated. Where such substitution occurs throughout the outcrop of a tilted formation it does not at all follow that it has taken place throughout the formation. Indeed, in the majority of the districts of the Lake Superior region it is probable that the segregation of chert extends to only a very limited depth. Where the chert is thus segregated by descending waters the source of the material may still be mainly chert of organic origin originally disseminated through the carbonate.

Where there are rather extensive formations of chert in a horizontal position, or nearly so, interstratified with beds of limestone or shale, the transportation of silica from material once above the plane of denudation by descending waters is not so likely to have been important. This is especially true of those cherts which are interstratified with shales, and therefore are protected from the surface waters by impervious formations. Hence such formations are more likely to be in large part the direct products of organic precipitation. While bunchy deposits of chert having no great lateral extent may often be produced by chemical precipitation, it is certain that such deposits may also be produced by direct organic precipitation.

This is illustrated by the chert deposits of the Franciscan series of California. These are regularly bedded deposits, locally of considerable thickness. They are lenticular and have an extremely narrow lateral extent. Often a deposit having considerable thickness disappears within a short distance. If a bunchy character be regarded as evidence of chemical origin it would be concluded that the Franciscan cherts are chemical deposits, and this was Lawson's conclusion.[a] Yet Lawson states that these cherts contain very numerous radiolaria; but this fact does not prevent him from suggesting that they are mainly due to local precipitation, in the bed of the ocean, of silica from silica-bearing springs. Lawson explains the abundant radiolaria as a coincidence. He says, in these deposits "radiolaria remains became embedded as they dropped to the bottom."[b] It

[a] Lawson, A. C., Sketch of the geology of the San Francisco Peninsula: Fifteenth Ann. Rept. U. S. Geol. Survey, 1895, pp. 420–426.

[b] Lawson, cit., p. 426.

seems to me that this is hardly a satisfactory explanation of the very abundant radiolaria which compose a considerable proportion of the deposits. If Hinde's argument as to the organic origin of the cherts which contain sponge spicules be correct, it probably follows that the radiolarian cherts of the Franciscan series of California are also organic deposits.

Another very interesting occurrence of chert is that of the whetstones of Arkansas. These are associated with clay shales[a] rather than limestones. They were regarded by Griswold as fragmental,[b] and therefore not belonging to the class of cherts at all, but to the novaculites. But Rutley has shown that these rocks contain no evidence of clastic origin, and have all the characteristics of cherts.[c] He regards them as replacement deposits of dolomite or dolomitic limestones. As this chert formation is somewhat persistent, and is between shale beds which are rather impervious, I am inclined to believe that it may be largely an organic precipitate, although now completely recrystallized, so as to be composed of perfectly fitting granules of quartz.

FRAGMENTAL CLASS.

PSEPHITE ORDER.

The psephite order includes pebble, gravel, and bowlder deposits, conglomerates, schist-conglomerates, and gneiss-psephites. (Pl. VIII.)

PEBBLE, GRAVEL, AND BOWLDER DEPOSITS.

The psephites form below bodies of water and also on the land. The chief body of water which deposits psephites is, of course, the ocean, although lakes and inland seas are by no means unimportant. The psephites in standing bodies of water are mainly formed along shores, where the wave action is vigorous, but to some extent they occur at the mouths of streams which are rapid until they reach the standing bodies of water. The psephites formed on the land are the till deposits of glaciers, especially the extensive formations of continental glaciers, and the coarse

[a] Griswold, L. S., Whetstones and the novaculites of Arkansas: Ann. Rept. Geol. Surv. Arkansas for 1890, vol. 3, 1892, pp. 205–206.

[b] Griswold, cit., pp. 168–194.

[c] Rutley, Frank, On the origin of certain novaculites and quartzites: Quart. Jour. Geol. Soc. London, vol. 50, 1894, pp. 377–392.

deposits of streams. These stream deposits are especially well illustrated in semiarid regions. For instance, at the present time large masses of psephites are found at the mouths of canyons adjacent to the mountains of the Great Basin, southern California, etc.; and Davis, Emmons, and Cross regard it as probable that other extensive psephite formations of the Cordilleras are fluviate.[a]

The material composing the psephites is not at all, or but roughly, assorted. Consequently, with the coarse material, there is a considerable amount of rather fine material to which the term psammite is applicable, and of still finer clayey material belonging to the pelite order. Commonly, however, the major part of the pelitic material is abstracted from the psephitic material by the water. This takes place to a greater degree in those deposits laid down under water than in those laid down under air.

The material of the psephites is but poorly sorted mineralogically. This is a necessary consequence of the large size of the fragments. The majority of the larger fragments are composed of two or more minerals. If the rock against which the waves are beating is granite, the pebbles contain all the minerals of the granite. The same statement is true in reference to all other classes of igneous and sedimentary rocks which are not readily broken into fine débris. But in some instances the majority of the pebbles may be composed of a single mineral. The most frequent illustration of this is furnished by quartz. Finally, any of the original igneous or sedimentary rocks may be in any stage of alteration, and such complex mineral material constitute the pebbles, provided the alteration is not of such kind that the material breaks down into its individual mineral particles.

It follows from the foregoing that the psephites have the greatest possible variation in mineral and chemical composition. An organic or chemical precipitate or an indurated clastic rock may be a chief constituent, quartz may be a chief constituent, any igneous rock may be a chief constituent, any metamorphic rock may be a chief constituent, or any of these various materials may be united in any proportion.

As rock masses, individual deposits of psephites are very common. Ordinarily these masses are not extensive in area, although sometimes they

[a] Davis, W. M. (with discussion by S. F. Emmons and Whitman Cross), Continental deposits of the Rocky Mountain region: Bull. Geol. Soc. America, vol. 11, 1900, pp. 596–604.

are. Generally they are of but moderate thickness. The psephite deposits made by standing bodies of water are usually in narrow bands adjacent to the shore, and, moreover, occur only locally along the shore. Where, however, a body of water steadily transgresses over the land, as, for instance, the ocean, a continuous formation of psephite over an extensive area may be deposited. Such a formation, while continuous, is not of the same age throughout. The earlier portion of a formation is usually buried under other sediments by the time the later part of the formation is deposited. Usually such psephites are not very thick formations—that is, hundreds of meters—for, as the land subsides and the sea transgresses, the waves can not transport the coarse material back to the areas where earlier psephites were deposited; consequently they are buried under finer material. The psephite deposits of continental glaciers may be very extensive and of considerable thickness. But psephite deposits of this class found among the older rocks are not very numerous. This may be partly due to their destruction by later geological action. The psephite deposits of fluviate origin, while usually of rather local extent, may be of considerable thickness, often from one hundred to several hundred meters. How far deposits of this origin are represented among the older formations which have been buried by later deposits it is difficult to say.

CONGLOMERATES.

Pebble, gravel, and bowlder deposits, by consolidation, cementation, and metasomatism, are transformed to conglomerates. (Pl. VIII, *A*.) These processes take place in the belt of cementation. The rocks here considered are so coarse that consolidation due to pressure in the belt of cementation produces comparatively little effect, since the coarse fragments have comparatively few points of contact. The process of cementation is identical with that of the psammites, described below. Since the psammites are more important than the psephites, the process of cementation is more fully discussed under that head. Because of the very great variety of material composing the psephites upon which the ground waters are acting, there may be a great variety of minerals deposited in the interstices. But the most abundant cement is usually quartz. Next in importance to quartz are iron oxide and the carbonates. In some cases hornblende, feldspar, etc., may be of consequence.

The amount of material required to cement the psephites is usually not nearly so great as that required to transform pure quartzose sands to quartzite. The reason for this is that the material is of such varying sizes that the spaces between the larger blocks are largely filled by finer materials. Also the fine material varies greatly in size. Consequently the amount of original pore space is frequently but a fraction of that of the even-grained sandstones. But in some instances the amount of fine material is not great, and the pore space is correspondingly large. Such deposits are illustrated by the psephites at the mouths of canyons of the West, which are so porous as to permit the absorption and transmission of vast quantities of water.

During the process of cementation metasomatism may take place. As already noted, there is great variety in the composition of the psephites, and any rock-making mineral may be present. From these there may be produced a great variety of secondary minerals—in fact, any of the minerals mentioned as characteristic of the belt of cementation. (See pp. 621–627). These minerals may be mingled with secondary minerals formed before the material was built into a psephite. It is frequently difficult or impossible to discriminate the alterations which occurred while the minerals were in the primary rock from those which took place after the minerals were in the secondary rock.

The question now arises as to where the processes of transformation of pebble, sand, and bowlder deposits to conglomerates take place. May a considerable part of the work be done for those rocks which are deposited below water before they emerge from it, or is the work in all cases mainly accomplished when the rocks are below land areas? It is, of course, possible, and indeed probable, that cementation and metasomatism, the important processes in induration, take place to some extent below the sea. However, it is not thought that these processes are there important. One reason for this belief is the certainty that circulation of the waters of the ocean must be comparatively slow through the sediments at the bottom; and it has been explained on pages 571–572, 866–868, that to dissolve and transport a large quantity of mineral material requires a vigorous circulation. A second reason for this belief is that while psephite deposits are still below the sea they have above them no belt in which weathering is taking place, and therefore no belt from which solutions steadily supply material for

cementation. But it should be stated that the psephites are the most favorable of all mechanical deposits for alteration below the water. This follows, first, from their coarseness, which is ordinarily such as to furnish openings of supercapillary size in which the resistance to water circulation is comparatively small; and, second, from the great variety of readily alterable minerals which they contain. The alteration of these minerals by oxidation, hydration, and carbonation, resulting in increase of volume, might supply considerable quantities of material to cement the interstices of the rocks without additions of any material from an outside source, and therefore not require vigorous circulation for its accomplishment. But, as already stated, it is believed that the main work of induration is accomplished after the rocks have emerged from the sea and erosion has begun. After arising from the sea, with differences of elevation, a vigorous underground circulation is set up; material is steadily contributed from the belt of weathering; consequently the processes of cementation and metasomatism take place with comparative rapidity, and thus transform the unconsolidated pebbles, gravels, and bowlders to conglomerates.

Where indurated conglomerates pass into the zone of anamorphism they may be further altered by the reactions of that zone. Where the conditions are mass-static the alterations do not obliterate previous textures and structures, and therefore the rocks remain conglomerates. But recrystallization of matrix and pebbles alike may take place on an extensive scale by silication and dehydration, with the production of the heavy anhydrous minerals characteristic of the zone of anamorphism.

SCHIST-CONGLOMERATE AND GNEISS-PSEPHITE, OR CONGLOMERATE-SCHIST AND PSEPHITE-GNEISS.

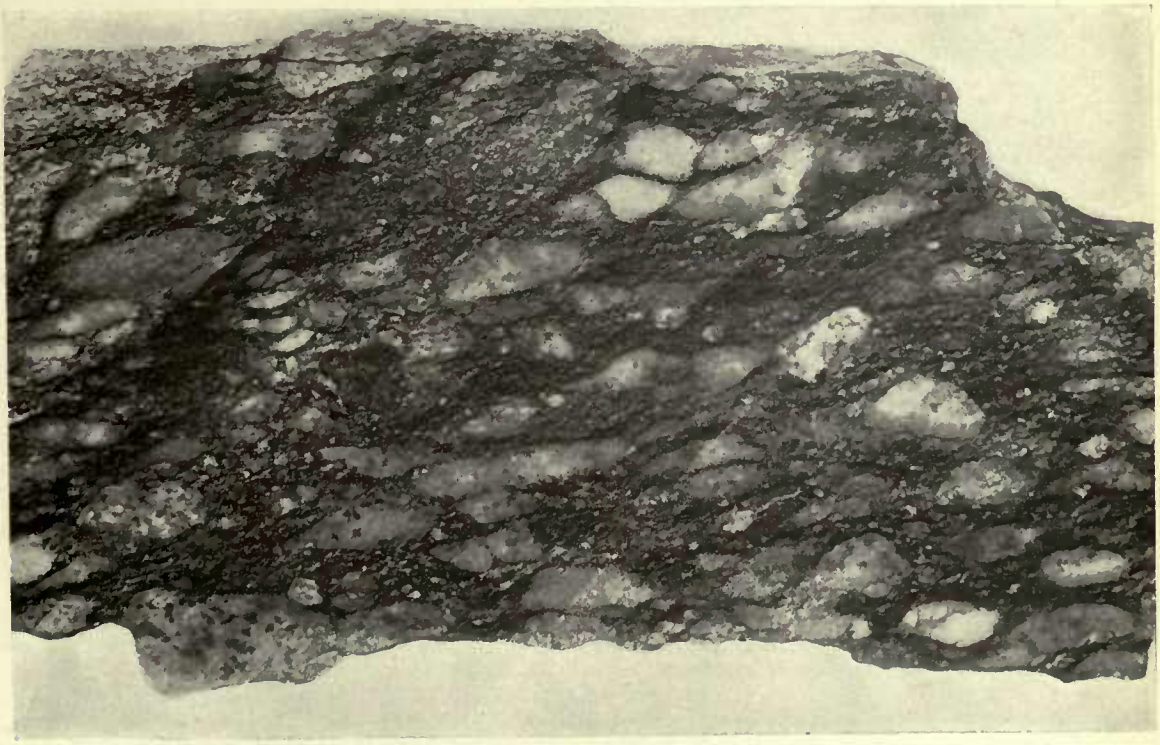
Where any of the previously described psephites—i. e., pebble, gravel, and bowlder deposits, or conglomerates—pass into the zone of anamorphism and are there subjected to mass-mechanical action, recrystallization and granulation, and the development of a schistose structure, take place under the principles described in Chapter VIII. (See pp. 685–696.) Because of the great variety of minerals which may be present in the psephites, all the minerals which develop in the lower zone under mass-dynamic action may form, and they may be most intimately intermingled. In general, the process of recrystallization and granulation is complete for the matrix at a stage when the pebbles are still very distinct, although, of course, in such

cases they are usually flattened and more or less granulated and recrystallized. At the same time a schistose structure develops in the matrix, and a schist-conglomerate or conglomerate-schist is thus produced. (Pl. VIII, *B*.)

Where the mass-mechanical movement is very severe the pebbles may be flattened into laminæ. Since material does not readily migrate in the zone of rock flowage, each pebble passes into minerals which may be derived from it. If there are different kinds of pebbles, it follows that there are various layers composed of different combinations, or at least different proportions, of the same minerals. Large bowlders may be observed in different stages, from oval forms, through greatly elongated and widened fragments, to forms in which the greatest diameters are several times the normal. (Pl. VIII, *A* and *B*.) Such a rock, when broken parallel to the direction of greatest flattening, appears to be a perfect schist or gneiss, but at right angles to this direction still plainly shows its conglomeratic character. As the process goes on the pebbles and bowlders are flattened more and more, until they become thin, lenticular masses, perhaps scarcely thicker than cardboard, or even like sheets of paper of great size. Wherever there was a quartz pebble there is apt to be a lamina composed of a quartz aggregate. Wherever there was a granite pebble there is usually a lamina in which mica has abundantly developed, and therefore one composed of mica, quartz, and feldspar. In many cases in which the process of transformation is nearly complete one may fail altogether to recognize the laminæ as pebbles in masses split parallel to the direction of greatest elongation; but when a specimen is cut in a direction transverse to this the pebbles distinctly appear. When the process has gone as far as this the material of the pebbles becomes so mingled with that of the matrix that it is difficult to exactly define the outlines of the fragments. Finally, as the process continues, no evidence of the pebbles and bowlders is left. In their places are thin laminæ of material of a mineralogical character different from that of the adjacent laminæ.

At the same time the bowlders are being transformed the matrix is also being recrystallized. At various steps of the process the matrix may be, in turn, slate, schist, and foliated schist. Before the pebbles are destroyed the foliæ of the matrix wind in and out, remaining approximately parallel to the nearest pebble, which acts as a transmitter of force. In proportion as the process continues, and the pebbles and bowlders approach oblitera-

A. UNALTERED NEWARK CONGLOMERATE FROM VIRGINIA. AFTER KEITH.



B SCHIST CONGLOMERATE FROM FELCH MOUNTAIN DISTRICT, MICHIGAN.

tion, the mineral particles more nearly approach a parallel orientation, instead of a part of them winding in and out about the more refractory particles. (See pp. 760–762.) Thus, by the granulation and recrystallization of the pebbles and matrix alike, with the consequent development of schistose and banded structures, a rock is produced to which the term gneiss-psephite or psephite-gneiss is applicable. (See pp. 782–783.)

Such a rock may be composed in various proportions of any of the minerals which form in the zone of anamorphism, as listed in Chapter V (pp. 363–364). This follows from the fact that the matrix and the pebbles of the psephites may be derived from all kinds of rocks, from the most basic to the most acid, from the volcanics and the plutonics, and from all varieties of metamorphic rocks. Therefore the rocks may have chemical compositions which vary from those of the original igneous rocks to those of mud, in which certain elements, and especially alkalies and alkaline earths, have been depleted. From the great variety of chemical compositions of the psephites it follows that any of the minerals may develop in them which are subsequently spoken of as forming in the schists and gneisses which belong to the psammite and pelite orders. While there is a very great variety of secondary minerals in the schists and gneisses of the psephites, in any given case two or three of these minerals are apt to be preponderant; and a given psephite-gneiss may be exactly designated by prefixing the names of the chief mineral constituents, as explained on page 783.

A very characteristic feature of the gneiss-psephites is the parallel orientation of the mineral particles, which gives the rocks cleavage. This characteristic is almost, if not quite, universal with the schists and gneisses which are derived by the metamorphism of sedimentary rocks, and thus serves in many cases as a criterion by which one may separate the original gneisses of igneous origin from those produced by metamorphism.

Some of the best known illustrations of schist-conglomerates and gneiss-psephites are those described by Hitchcock[a] many years ago, those of the Hastings district of Canada,[b] those of various places in the Lake

[a] Hitchcock, Edward, Hitchcock, Edward, jr., Hager, A. D., and Hitchcock, Charles H., Report on the geology of Vermont, vol. 1, 1861, pp. 28–45. Whittle, C. L., The occurrence of Algonkian rocks in Vermont, and the evidence for their subdivision: Jour. Geol., vol. 2, 1894, pp. 422–429.

[b] Adams, F. D., and Barlow, A. E., On the origin and relations of the Grenville and Hastings series in the Canadian Laurentian, with remarks by R. W. Ells: Am. Jour. Sci., 4th ser., vol. 3, 1897, pp. 173–180.

Superior region,[a] and those of Hoosac Mountain, western Massachusetts.[b] In each of these localities, where the mashing was not so severe as the average for the formation, the rocks are not metamorphosed beyond the stage of schist-conglomerate, and thus give evidence that the gneiss-psephite continuations of these rocks have been produced from sediments.

One of the very best illustrative localities is that of the Vermont formation of Hoosac Mountain, described by Wolff.[c] In this formation every stage of gradation from a distinct and unmistakable schist-conglomerate to gneiss may be seen. Another excellent illustration which shows intermediate stages between the conglomerate and the gneiss is that of the Sturgeon River tongue of the Crystal Falls iron-bearing district of Michigan.[d] Here the matrix is completely recrystallized, and if it were not for the pebbles would be unhesitatingly called a gneiss. But the pebbles are in an intermediate stage of destruction, being considerably flattened, though still very distinct. The upward continuation of this formation, in which the fragments were small, shows no evidence whatever, by texture or structure, of its original clastic character, either in the field or under the microscope. It is a completely recrystallized quartz-feldspar sand which has become a psammite-gneiss. (See pp. 875–876.)

PSAMMITE ORDER.

QUARTZ-SAND FAMILY.

The quartz-sand family (Pl. IX) includes quartz-sand rock, sandstone, quartzite, and schist-quartzite.

QUARTZ-SAND ROCK.

Quartz-sand rock is an unconsolidated deposit or formation composed mainly of grains of quartz. Quartzose sands are one of the most common and widespread of the mechanical sediments. The origin of such sands is so well understood that little need be stated as to this part of the subject.

---

[a] Van Hise, C. R., and Bayley, W. S., The Marquette iron-bearing district of Michigan, with a chapter on the Republic Trough, by H. L. Smyth: Mon. U. S. Geol. Survey, vol. 28, 1897, pp. 294–298, 434–437, 477–479. Clements, J. Morgan, and Smyth, H. L., with Bayley, W. S., and Van Hise, C. R., The Crystal Falls iron-bearing district of Michigan: Mon. U. S. Geol. Survey, vol. 36, 1899, pp. 474–476.

[b] Pumpelly, Raphael, Wolff, J. E., and Dale, T. Nelson, Geology of the Green Mountains in Massachusetts: Mon. U. S. Geol. Survey, vol. 23, 1894, pp. 48–59.

[c] Wolff, cit., pp. 48–59.

[d] Mon. U. S. Geol. Survey, vol. 36, cit., pp. 474–476.

Wherever coarse mechanical sediments are contributed to the sea by streams, quartz-sand grains are present. Wherever the sea is at work upon the shore, quartz sand is one of the products. At all places where the bodies of water are of a large enough size to produce waves of considerable power—that is, in large bays and along the border of the open ocean—the process of mechanical sorting takes place, by means of which the quartz-sand grains are separated from other minerals. This follows from the difference in specific gravity, size, and shape between the grains of quartz and those of other minerals. Not only are the quartz-sand grains sorted from feldspar, hornblende, and similar minerals, but the quartz sands are sorted according to size, as a result of which in one place the grains of sand are rather large, perhaps averaging 1 to 5 millimeters in diameter, while in other places they are very small, averaging as low as 0.1 to 0.05 millimeter. Of course there are all gradations between deposits of different coarseness, and also between pure quartzose sand deposits and those in which other minerals are important or dominant.

However, the frequent almost perfect sorting of the quartz grains from other material, and the arranging of the quartz grains of nearly uniform size together, is a matter of constant surprise. Great formations of sand rock are produced which have not more than 2 or 3 per cent of other minerals besides quartz, and some which have not so much as 1 per cent of any other mineral. Moreover, in some formations, the ratios of the diameters of but few of the grains is as great as 1 to 2, and the majority of the grains do not vary by as much as a third of a diameter. Both the advanced condition of the sorting and the uniformity of the size of the grains are well illustrated by the St. Peter sandstone of Wisconsin. Specimens of this sandstone show but few particles of any other mineral than quartz.

Mr. Sydney H. Ball made for me a considerable number of measurements of the grains of this sandstone from two different localities. From one locality 25 grains were measured, which gave as the average greatest diameter 0.3388 mm., and as the average least diameter 0.2964 mm. Of these grains 21 have major diameters ranging between 0.20 and 0.50 mm., of which 14 are between 0.25 and 0.45 mm. Of the grains measured, 21 have minimum diameters between 0.20 and 0.50 mm., and of these, 14 are between 0.25 and 0.45 mm. The maximum and minimum lengths and breadths for individual grains are 0.54 and 0.16 mm., and 0.50 and 0.14 mm.,

respectively. From another locality 11 measurements of sandstone grains gave an average greatest diameter of 0.2009 mm., and an average least diameter of 0.1463 mm. At this locality all but 2 of the major diameters are between 0.15 and 0.37 mm., and all but 2 of the minor diameters are between 0.16 and 0.23 mm. The maximum and minimum lengths and breadths of any individual grain are 0.37 and 0.10 mm., and 0.32 and 0.08 mm. The above measurements for each of these rocks show a remarkable approximation to a spherical form for most of the grains, and an almost astonishing uniformity of size for the great majority of the grains, although an occasional grain varies considerably from the average in size.

Besides sand formations which are deposited below the water, sand formations are built up below the air. The most important of these are dunes, the material of which is derived from the sands sorted by the water along the shore. The wind picks up this sand, carries it inland, and thus builds up along large bodies of water, especially such bodies as the Great Lakes and the ocean, very considerable deposits which are similar in material and arrangement to the sands deposited by water. Such sand formations are, however, more variable in thickness and more limited in extent than sands deposited under the water. In the interior, especially in desert regions, formations of quartz sands may occasionally be built up independently of water, but, in general, interior wind-deposited sands are not well sorted, and consequently contain as abundant constituents other materials than quartz. Therefore such deposits ordinarily do not belong in the quartz-sand family, and they are considered on pages 877–878.

Since quartz is second in abundance only to feldspar as a constituent of the original igneous rocks, since it is extensively manufactured from the silicates by the processes of metamorphism, and since, unlike many other minerals, it does not readily dissolve or unite as a solid with other minerals, one would expect that very extensive formations of quartz sand would be produced; and to such expectation the facts correspond. Almost every inland lake is building up a belt of quartz sand of greater or less width along the shore. The width of this belt is, of course, dependent upon the size of the lake and upon the depth of the water. The greater the lake the wider is the sand belt, the coarser sands being near the shore and the finer ones farther from the shore. Gradual deepening of the water also is

favorable to a broad belt, for in that case the undertow is effective farther from shore than where the waters are deep. The rule as to gradual increase in depth applies to the ocean where the shore is swept by the full force of the waves. In bays the building up of quartzose sands is largely dependent upon the amount of material contributed to it. If, for instance, a great river flows into a bay of moderate size, the amount of material of all kinds is so great that the wave action is not sufficiently vigorous to sort the material, and pure quartz-sand deposits are not formed. It appears probable that in the past the most extensive quartz-sand formations have been the deposits of moderately shallow waters in great mediterranean seas, as, for instance, the Cambrian sands of the interior basins of the United States. These sands constituted thick deposits in the Appalachian Mountain system, the southern part of Canada, and throughout the entire northern part of the United States. In the western part of the United States almost equally extensive sand formations have been produced In order that thick sand formations shall be built up below the water, it is, of course, necessary that subsidence shall take place concurrently with the deposition. In this respect one rock formation does not differ from another.

If the sand grains be supposed to be of uniform size and spherical, and to be arranged in the most compact system geometrically possible, the space occupied by the sand grains is 74 per cent, and the space between the grains is 26 per cent, of the entire space occupied by the formation. (See Chapter III, p. 125.) As shown by Buckley,[a] in the Dunnville sand rocks, which have been partially indurated, the space is found to be as great as 28 per cent. The explanation of this lies in the fact, discovered by Professor Slichter, that under natural conditions sand grains are never arranged in the most compact manner possible. Ordinarily this fact more than compensates for the varying size of the grains and their imperfect spherical shape (see p. 126); and it may be regarded as certain that the quartz grains of well-sorted pure-sand formations, such as the St. Peter sandstone of Wisconsin (see p. 861), occupy not more than two-thirds to three-fourths of the space.

[a] Buckley, E. R., Building and ornamental stones of Wisconsin: Bull. Wisconsin Geol. and Nat. Hist. Surv. No. 4, 1898, p. 225.

SANDSTONE.

Sandstone is indurated quartz-sand rock. The induration is sufficient to make the grains of sand rather strongly coherent, but not so great that the grains break across when the rock is fractured; on the contrary, the fractures follow the cement around the grains. The change of a sand formation to a sandstone is due to consolidation and cementation. These processes are characteristic of the belt of cementation. The process of consolidation by pressure is of relatively little importance in sandstones. Slichter has shown that sands as naturally deposited by water are likely to have a tolerably compact arrangement,[a] and that mechanical disturbance of such sands is likely to result in a less compact arrangement. Sand grains, while having many more points of contact than psephites, have few as compared with the finer grained sediments. Doubtless the superincumbent pressure does bring these grains into juxtaposition, and may possibly weld them to some extent at the points of contact, but sands in which this process alone has occurred are sure to be very weak.

The main process of induration is that of cementation. (See Pl. IX, *A*.) Silica is dissolved in the belt of weathering, either by the decomposition of silicates or by the solution of silica, either amorphous or crystallized. The solutions join the sea of ground waters, and there the silica is deposited upon the sand grains, usually in optical orientation with them. The result of this process is to partially fill the spaces between the sand grains. These filling materials after a time interfere and thus cement the sand grains together. In so far as they do not interfere, the added material is likely to develop crystal faces, and thus there are produced crystal-faceted sand grains, which together make up the sandstone. Sandstones the world over are mainly thus indurated, and ordinarily show innumerable crystal faces when a specimen is held so that the light of the sun may be reflected. While quartz is the dominant cement, iron oxide and calcite are often important cements, and many other minerals are unimportant supplementary cements. Rocks indurated by cementation are usually called sandstones from the time the cementation is sufficient to make the grains weakly cohere to the stage in which the cementation is far enough advanced to cause the rock to break across the sand grains rather than around them. At this later stage they become quartzite.

[a] Slichter, C. S., Theoretical investigation of the motion of ground waters: Nineteenth Ann. Rept. U. S. Geol. Survey, pt. 2, 1899, p. 305.

The question as to where the process of cementation from sand to sandstone takes place is discussed under the next heading, "Quartzite," since the problem is precisely the same with both, and it can be better understood after the facts relating to the cementation of quartzites have been considered.

QUARTZITE.

One of the most important rocks produced by the cementation process is quartzite. (Pl. IX.) The term "quartzite" is here restricted to quartzose sand rocks which have been so firmly indurated by the cementing processes that when broken the fractures pass through the original grains and not around them. The process of cementation continues, until the enlarged sand grains or the independent quartz deposited interfere and interlock so as to nearly or quite fill the interspaces. (Pl. IX, *B*.) In the production of indurated sandstone and quartzite the quartz may be deposited either as enlargements of old grains or as independent interstitial material. In either case the induration may be so nearly perfect that a vitreous quartzite is produced. If composed of very fine grains of sand, so that the indurated rock may serve as a whetstone, the rock has been called novaculite. Novaculite is therefore no more than an even- and fine-grained quartzite. In general, there is a strong tendency for the quartz to deposit upon the old grains rather than as independent mineral particles. The reason for the deposition of the quartz from the solutions and the optical orientation of this quartz with the original sand grains has been discussed on pages 75–76, 121–123. It may here be said in summary that the explanation lies in the power of a mineral to abstract from solutions material like itself, for large particles to grow rather than new ones to develop, and to the fact that silica is one of the most abundant of the materials which are transported by ground waters. Many of the cemented quartzites show little or no evidence of strain, which proves that mechanical action has not been potent in the induration. Neither is there any evidence that a high degree of heat is requisite to dissolve the silica or to deposit it as quartz upon or between the old grains. The sands from which quartzites develop contain various impurities. During the transformation of the sands to quartzite these impurities are rearranged to a greater or less extent by metasomatic changes and new minerals develop, as described in the cases of the minerals in the feldspathic sands and the grits. (See p. 870 et seq.) As with sand-

stones, so in quartzites, iron oxides and calcite are subordinate cements, and frequently other minerals to some extent perform a similar function. In many parts of the continents the process of cementation has transformed sandstone to quartzite for extensive areas, many such formations of widely differing geological ages covering hundreds of thousands of square kilometers. These quartzite formations vary in thickness in different places from a few meters to as much as 3 or 4 kilometers.

It has been seen under "Quartz-sand rock" (p. 863) that ordinarily the material of well-sorted, pure sand formations does not occupy more than two-thirds to three-fourths of the space. This requires that in the cementation of a sand to a quartzite from one-fourth to one-third of the formation be added by the ground waters. It is therefore certain that the amount of secondary silica required to indurate such great quartzite formations as occur in the Paleozoic and pre-Paleozoic of the continent is enormous. That required for vein fillings, while vast, is probably inconsiderable as compared with this.

For instance, if a quartzite formation were supposed to have a volume of 100 cubic kilometers, to change this rock from a sand to a quartzite would require the addition of from 25 to 33 or more cubic kilometers of quartz. It would be very interesting to make an estimate as to the amount of quartz which has been added by the ground circulation to the quartzites which are now known to exist, but the descriptions of quartzite formations are not sufficiently accurate to admit of even an approximate estimate of their volume. However, certainly many thousands, and probably hundreds of thousands, of cubic kilometers of quartz must have been added by the ground solutions in order to indurate these formations. It has been fully explained on pages 480, 516–517 that the silica liberated from the silicates by the process of carbonation in the belt of weathering is entirely adequate to account for much or all of the silica supplied by the ground waters.

There remains to be considered the question where the process of cementation of sand to sandstone and quartzite takes place. If the argument given on pages 856–857 in reference to the minor importance of the cementation of psephites below the sea be correct, it is still more applicable to the cementation of sands. Murray and Renard have estimated that sea water contains in solution, on the average, only one part of silica in 250,000

parts of water.[a] The openings between sand grains are of capillary size. The circulation of the sea water through sandstone formations below the sea where there is hydrostatic equilibrium must be exceedingly slow; indeed, is probably negligible. In the case of sandstones there is no way by which recrystallization may cement the material, as with the psephites, which contain minerals capable of expansion reactions. The sand grains are composed of quartz, and quartz is required for cementation. There is no belt of weathering, the material of which is being continuously dissolved and transported to the belt of cementation below. For the above reasons it is thought that the cementation of sandstones, while still below the waters in which they were deposited, is negligible. If this be true, the cementation of sands must take place after they have been raised above the sea and an underground circulation has been established. Even after these conditions exist, and the conditions are favorable to a vigorous underground circulation which steadily derives from the belt of weathering large quantities of silica, cementation is still very slow.

It has been seen that the amount of silica required to indurate the great quartzite formations is enormous. The vastness of the geological work of this kind probably gives us the best measure of the extent to which ground waters have circulated and the enormous amount of water which must have passed through these formations before the cementation is complete.

The numerous analyses of mineral spring waters, more than ordinarily rich in soluble compounds, show that such waters do not contain, on the average, more than one part by weight of silica in 100,000 to one part in 10,000. This latter amount is exceeded by only a few wells or springs, such as the Humboldt salt well.[b] Supposing that the underground water which passes into the belt of cementation steadily carries one part in 50,000 of silica by weight, and that all of it is deposited, the filling of a pore space amounting to one cubic kilometer would require the circulation of 50,000 times 2.6, or 130,000, cubic kilometers of water.

Even for the cementation of a single formation, such as that of the quartzite of the Penokee-Gogebic iron-bearing district of Michigan and

---

[a] Murray, John, and Renard, A. F., Deep-sea deposits: Report on the scientific results of the voyage of H. M. S. *Challenger*, 1873–1876, London, 1891, pp. 286–288.

[b] Peale, A. C., Lists and analyses of the mineral springs of the United States: Bull. U. S. Geol. Survey, No. 32, 1886, p. 159.

Wisconsin, where there is a quartzite formation 130 kilometers long and 120 meters wide, the amount would be enormous. Supposing the induration to have extended only to the depth of 2 kilometers along the dip, the amount of water which must have passed through this formation in order to have cemented it would be 4,056,000 cubic kilometers. Thus the cementation of this single formation required the circulation of almost incredible quantities of ground water; and the addition of the almost indefinitely greater quantity of quartz cementing the quartzite formations now existing would require a correspondingly greater amount of water.

Even this point of view does not give a conception of the amount of ground circulation required to cement the quartzites; for during geological history probably a great many more quartzite formations than now exist have been produced and destroyed by the processes of erosion. And in the quartzites we have but a single phase of the work of ground water. It therefore follows that the amount of ground water required to cement a single formation is infinitesimal as compared with the amount which has circulated through the rocks during geological ages. Indeed, it is probably not too much to say that the same water has circulated through the ground more than once, for it is doubtful whether the entire volume of the water of the ocean is sufficient to have done the work of cementation and metasomatism by use a single time.

SCHIST-QUARTZITE OR QUARTZITE-SCHIST.

A schist-quartzite or quartzite-schist is a quartzose rock derived from a sandstone or quartzite which has a more or less well-developed schistose structure. These rocks are produced in the zone of anamorphism under mass-mechanical conditions. Granulation or recrystallization, or both, are the dominant processes, but with these, welding and cementation are at work. In order to produce a schist-quartzite it is not necessary to suppose that cementation has filled the entire spaces between the sand grains; for mashing, resulting in granulation, recrystallization, and welding may so rearrange the material as to close the openings and lessen the volume of the rock, with no added material from an outside source. Therefore it can not be assumed that any considerable amount of material has been added to schist-quartzites, unless evidence remains in the enlargements of the quartz grains. Not infrequently in the schist-quartzites such evidence may be seen. In the least mashed phases of schistose quartzites the quartz

grains may be but slightly fractured. In passing to more mashed varieties regular lines of fracture occasionally appear at right angles to each other. As the mashing becomes more advanced, granulation begins. This first affects the exteriors of the grains, but as the process continues the grains may be granulated throughout. (Pl. IX, *D.*) Generally, however, before granulation is far advanced recrystallization begins. As a result of this, in the interstices new quartz and mica develop (the latter from the impurities) and the recrystallization of the old grains of quartz occurs, as described on page 865. Recrystallization checks, and finally reverses, the tendency of granulation to produce finer and finer particles. Where recrystallization becomes important, and especially where it becomes dominant, the mineral particles may grow to a relatively large size. In proportion as a mass is deep seated and the mashing is extreme there is a marked tendency to a parallel dimensional arrangement of the newly crystallized particles (see pp. 688–689, 760), and the final process is a schist-quartzite or quartzite-schist which shows no sign of fragmental origin. In many instances the coarser quartzite-schists have particles averaging 7 mm. in length and 4 mm. in breadth. The common ratio between minor and major diameters, as ascertained by Leith, varies from 20:100 to 100:100, with an average of perhaps 50:100.[a]

The schist-quartzites and quartzite-schists which are largely readjusted by recrystallization beautifully illustrate the principle that this process lags behind mechanical deformation. (See Chapter VIII, pp. 696–698.) Residual strain effects, as shown by strain shadows, are very general. Occasionally, however, the entire rock has largely recrystallized under static conditions after mashing ceased, and there has been produced an interlocking granular quartz rock in which the quartz particles have no similar dimensional orientation and in which there is little residual strain effect. This peculiar variety is beautifully illustrated by the quartz rocks of Rib and Mosinee hills, near Wausau, Wis. (Pl. IX, *C.*) After complete recrystallization has taken place, producing a granular quartz rock, when the rock is again deformed granulation may occur. This further change has locally taken place at Rib Hill. (See Pl. IX, *D.*)

In proportion as the sands, sandstones, and quartzites are impure the schist-quartzites and quartzite-schists forming from them will be impure.

---

[a] Leith, C. K., Rock cleavage.

From the impurities are apt to develop some of the heavy minerals of the zone of anamorphism. Of these minerals mica is by far of the greatest consequence, and of the micas muscovite is the most abundant. The secondary mica always shows a well-developed parallel arrangement, with its greater dimensions and readiest cleavage parallel to the greater dimensions of the quartz. These mica-bearing rocks are schistose, micaceous quartzites and micaceous quartzite-schists. While mica is the most frequent of the minerals which form in connection with the schist-quartzites, other minerals, such as tourmaline, actinolite, etc., may form, and if they become important they may give mineralogical qualifiers to the names schist-quartzite and quartzite-schist.

In some districts all stages of gradation from quartzites, through schist-quartzites and quartzite-schists, may be seen. These stages may be best observed in a region not too strongly folded on the crests and in the troughs of the folds. At such places there is comparatively little readjustment, while on the limbs of the folds, especially between the beds, the differential movements are much more marked. Therefore on the crests and in the troughs of the folds and in the center of the beds the less changed rocks are found, while at the outer parts of the beds and on the limbs of the folds schists may be formed.

QUARTZ-FELDSPAR-SAND FAMILY.

The quartz-feldspar-sand family includes quartz-feldspar sands, arkose, and schist-arkose or gneiss-arkose.

QUARTZ-FELDSPAR SAND.

Some fragmental formations are composed mainly of feldspar and quartz, and such deposits may be called quartz-feldspar sands. The most favorable conditions for their formation are those of disintegration of acid feldspathic rocks, with comparatively little decomposition, and contiguity to the sea. (See Chapter VI, pp. 496–501.) The more prominent rocks furnishing material for the quartz-feldspar sands are the granite and syenite families among the igneous rocks, and the acid gneisses and schists among the metamorphic rocks. The volume of these rocks is very considerable, and the acid feldspars, which are among their essential constituents, are slow to decompose. It follows that the quartz-feldspar sands occur in considerable volume. Feldspars from intermediate and basic rocks are in

PLATE IX

some instances important supplementary sources of material. Quartz and acid feldspars have very nearly the same specific gravity, and unless such material be gradually contributed to the water, so that it can be handled by strong waves and currents for a long time before final deposition, quartz and acid feldspar will not be separated. The basic feldspar is more apt to be separated. These conditions for imperfect separation especially prevail in bays and gulfs where the full power of the ocean is not felt. The only other important constituent of ordinary granite and of many of the acid schists and gneisses, beside quartz and feldspar, is mica. This mineral, because in flakes, is carried farther than the quartz and feldspar, and thus is easily and rapidly separated from them and transported to deeper water. Consequently, in the comparatively shallow waters along the shore many nearly pure quartz-feldspar sands may be built up.

One of the best illustrations of the deposition of quartz-feldspar sands at the present time is that in the Gulf of California, described by McGee.[a] The rocks of this region consist largely of granites and granitoid schists and gneisses, although mingled with them are various igneous rocks and tuffs. The region is one of great aridity and rapidly varying temperature. The small amount of rainfall is concentrated in thunder storms, in some cases of exceptional violence. The result is that the rocks which are disintegrated but not decomposed are transported by the process which McGee has called sheet-flood erosion. (See Chapter VI, p. 497.) The undecomposed material is piled up in the ravines of the mountains or is transported to the gulf by storms of exceptional violence. The waves of the gulf are at work upon such disintegrated material and the salients of the solid rock. Thus a large amount of material is furnished by the waves and streams, to be distributed by the shore currents and undertow. The final result is that the quartz and feldspar, with some mica, are deposited as a quartz-feldspar-sand formation. McGee notes that where there are prominent salients the quartz-feldspar sand is coarsest and cleanest, and that where there are recentrants there is mingled with the coarse quartz and feldspar a considerable proportion of finely comminuted materials.[b]

Doubtless this case of the formation of quartz-feldspar sands in the Gulf of California points to the conditions under which similar sands were

[a] McGee, W J, The formation of arkose: Science, new ser., vol. 4, 1896, pp. 962–963.
[b] McGee, cit., pp. 962–963.

deposited in the past, although other combinations of conditions may have produced similar results. For instance, where the sea has rapidly transgressed over a region of granitic rocks the material may be broken down by wave action and incompletely assorted, thus producing quartz-feldspar sands. Or great deposits formed in an interior basin may be overridden. Thus if by subsidence the sea should advance over the Great Basin of western United States (see Chapter VI, p. 559) at various places stratified feldspathic sands similar in character to those of the Gulf of California would be buried, since in this region there are various granitic and acid schistic, gneissic, and granitic mountain ranges about which the fieldspar and quartz débris of the mountains is being built up as stratified rocks by the streams and ephemeral lakes and by sheet flood erosion. But from such deposits neither mica nor any other mineral is more than imperfectly separated. Therefore, unless the original rocks were enormously rich in quartz and feldspar, such deposits are likely to contain with the quartz-feldspar sands considerable quantities of ferromagnesian sands, considered on pages 877–879.

ARKOSE.

Arkose is cemented quartz-feldspar sands. The arkoses are formed in the belt of cementation. The cementing material is largely quartz, just as with the quartz sands. Other cementing materials are calcite, ferrite, etc., and in some cases the cementing material is largely feldspar. This is well illustrated by the arkoses of the Keweenawan of the Lake Superior region. The rocks from which these arkoses were derived were the volcanic rocks of the Lower Keweenawan. In the Keweenawan arkoses the cementing material is mainly quartz, but this is occasionally supplemented by feldspar, and in some instances where the arkose is a nearly pure feldspar rock the feldspar interstitial material is the main cement. This feldspar is largely added to the feldspar grains in optical continuity, precisely as is the quartz to the quartz grains, thus enlarging them. Where the feldspars are twinned plagioclases, the enlargements are twinned in similar fashion.[a] (See fig. 14, p. 626.) These arkoses give one of the best illustrations of the capacity of mineral particles to abstract from the solutions material like themselves and add it to themselves. (See pp. 121–123.)

[a] Irving, R. D., and Van Hise, C. R., On secondary enlargements of mineral fragments: Bull. U. S. Geol. Survey, No. 8, 1884, p. 46.

The process of cementation may be partial, as with the sandstones, or may continue until the material has practically filled all the interspaces, as with quartzites, when the rock becomes completely indurated arkose. Where cementation is very partial, the rock fractures around the grains rather than across them, just as in a sandstone. Where cementation is complete or nearly so, the fractures are across the grains rather than around them, just as in quartzite, to which the rock is then analogous.

During cementation the feldspars in the arkoses may undergo metasomatic changes. The dominant feldspars are orthoclase, microcline, and the acid plagioclases. Any of the alteration products of these minerals characteristic of the belt of cementation may form, but the most abundant products of their alteration are quartz, chlorite, the zeolites, and the epidotes.

Where by deep burying the arkoses pass into the zone of anamorphism, the original feldspars or their alteration products are likely to recrystallize, producing heavy anhydrous minerals. Under such circumstances the acid feldspars are most likely to pass into quartz and mica. The alteration products of the feldspars produced in the belt of cementation may reproduce feldspar or may unite to form quartz and mica. In proportion as the quartz-feldspar sands were impure, the heavy minerals are likely to form. So long as the conditions are mass-static the original textures and structures of the rock are likely to be preserved; but if in the deep-seated zone the conditions are mass-mechanical, schist-arkoses or gneiss-arkoses, considered under the next heading, are likely to form.

The induration of the arkoses is believed to be mainly accomplished while the deposits are land areas. The reasons for this belief are the same as in the case of the sandstones. (See pp. 866–867.)

SCHIST-ARKOSE AND GNEISS-ARKOSE, OR ARKOSE-SCHIST AND ARKOSE-GNEISS.

After the arkoses are formed and have become buried deep enough to be in the zone of anamorphism, mass-mechanical action may take place. In consequence of this a schistose or gneissose structure is developed, and the rocks become schist-arkose and gneiss-arkose, or arkose-schist and arkose-gneiss. There are, of course, all gradations between the rocks here considered and the arkoses. Where the mechanical action is rather weak, a schistose structure is not marked. Where mass-mechanical action is

profound, a schistose structure is strongly developed. Where the original sands were of the same general character, schists are likely to be produced; where the sands were in alternate bands, some of which were mainly quartzose and others strongly feldspathic, a gneiss is likely to form. Such a gneiss is beautifully illustrated in the Sturgeon River tongue of the Crystal Falls district of Michigan, adjacent to the conglomerate-gneiss already mentioned.[a] (See p. 860.)

During the transformation the quartz is granulated and recrystallized, precisely as in the schistose quartzites. Since the feldspars of the arkoses dominantly belong to the acid end of the series, they usually break up into mica and quartz. So far as the feldspar is orthoclase or microcline, muscovite and quartz form. Where the arkose is impure, and magnesium and iron are present in considerable quantity, biotite is likely to develop. At the stage in which the alteration of the feldspar is partial there is an interlocking mixture of quartz, feldspar, and mica. In other words, at this stage the rocks have a composition which, under the German usage of the term, would be called mica-gneiss. Where among the feldspars intermediate varieties, such as labradorite and bytownite, are present, simultaneously with the development of the other minerals, albite, oligoclase, and andesine may form, but of these albite is by far the most prevalent. Thus out of the old feldspar a great deal of new and usually acid feldspar is produced. The development of new feldspar is particularly likely to take place when adjacent igneous intrusions have occurred, especially granitic intrusions. Doubtless the hot mass of granite promotes the formation of solutions which carry abundant feldspathic material, and out of this, in part at least, the new feldspar develops. (See pp. 713–715.) In the schist-arkoses the micas have well-developed parallel orientation, with their longer axes and cleavages in a common plane. The new feldspars may also have a similar orientation. Such an arrangement is beautifully illustrated in the Hoosac schist, described by Wolff.[b] In this rock, mainly composed of quartz, mica, and feldspar, the latter mineral, mainly albite, is wholly recrystallized and locally shows a very marked parallel orientation.

---

[a] Clements, J. Morgan, and Smyth, H. L., with Bayley, W. S., and Van Hise, C. R., The Crystal Falls iron-bearing district of Michigan: Mon. U. S. Geol. Survey, vol. 36, 1899, pp. 463–464.

[b] Pumpelly, Raphael, Wolff, J. E., and Dale, T. Nelson, Geology of the Green Mountains in Massachusetts: Mon. U. S. Geol. Survey, vol. 23, 1894, pp. 59–63.

FERROMAGNESIAN-SAND FAMILY.

The ferromagnesian-sand family includes the ferromagnesian sands, grits, graywacke, and slate-graywacke, schist-graywacke, or gneiss-graywacke.

FERROMAGNESIAN SANDS.

At many localities ferromagnesian sands are built up which are mainly composed of quartz, the feldspars, and the ferromagnesian minerals. With these dominant minerals there are subordinate quantities of various other minerals—in fact, any of the minerals which are important as rock constituents, with the possible exception of such readily decomposable soda-bearing minerals as sodalite, nephelite, etc.

The conditions for the deposition of the ferromagnesian sands are those of disintegration, with little decomposition. These conditions are fully discussed on pages 496–501. It is here only necessary to say that the conditions are substantially the same as those for the formation of the feldspar-quartz sands, except that the rocks from which the minerals are derived contain the ferromagnesian minerals abundantly. In proportion as the climate is arid, in proportion as the material has to be transported only a short distance, in proportion as it is coarse, in proportion as there is great change of temperature by insolation in the warm regions and freezing and thawing in the cold regions, the various igneous rocks are broken down. Thus, sands composed of individual grains or aggregates of grains of the same or unlike mineral composition are formed. The rocks from which the ferromagnesian sands are derived must contain abundantly the ferromagnesian minerals. These ferromagnesian sands are deposited under physical conditions very similar to those under which the quartz-feldspar sands are deposited.

The formations may be built up on land or below water. Where built on land in arid regions, thick deposits are likely to result, especially where there is no drainage to the sea. Such deposits are illustrated in the Sahara and in the Great Basin of western United States. The conditions for the formation of sands in such districts have been fully discussed by Walther,[a]

[a] Walther, Johannes, Die Denudation in der Wüste und ihre geologische Bedeutung, S. Hirzel, Leipzig, 1891, pp. 448–461. Walther, Johannes, Das Gesetz der Wüstenbildung in Gegenwart und Vorzeit, Dietrich Riemer, Berlin, 1900, pp. 31–52.

and have been alluded to in this treatise. (See Chapter VI, pp. 496–497.) Nothing further will be said upon their manner of formation. The essential point in this connection is that such sands are likely to be not at all, or very slightly, sorted; therefore they contain practically all the minerals of the original rocks from which they are derived, and hence include the ferromagnesian minerals. While such formations are of very great thickness in various parts of the world, and doubtless are now being indurated in their lower parts, as described below, it is difficult to ascertain how far the ferromagnesian sands, and their altered equivalents thus formed, have been preserved among the rocks of past geological ages.

Ferromagnesian sands are being extensively deposited below the waters of inland seas and of the ocean, where the sorting is very imperfect. This is likely to be the case in the estuaries or near the mouths of strong rivers which are rapid to their mouths. All these conditions are well illustrated by some of the rivers which flow into the estuaries of the Atlantic, such as the Susquehanna. The conditions for the deposit of ferromagnesian sands are still more nearly perfect along the Pacific coast. The rapid streams of the Coast Range carry the extremely varied material of the mountains to the bays, such as San Diego, San Francisco, and Puget Sound, or to the ocean. But in the open ocean the ferromagnesian sands are likely to be sorted into their constituent minerals.

While the perfect conditions for the formation of the ferromagnesian sands are those of disintegration with no decomposition, of course decomposition does everywhere occur to a greater or less degree. In the case of the rivers of the Piedmont plateau, which are emptying into estuaries, the decomposition of the sands is considerably advanced. But the decomposition of the sands of the Coast Range is not nearly so far advanced.

Since decomposition everywhere occurs to some extent, the ferromagnesian minerals and the feldspars have been changed more or less to minerals into which they commonly alter in the belts of weathering and cementation. The feldspars may have been changed in part to kaolin, mica, quartz, zeolites, etc. The pyroxenes, amphiboles, and biotite may have been changed to a greater or less extent to chlorite, epidote, serpentine, talc, etc. Thus in the sands under consideration there may be present not only original minerals, but any of their alteration products in various proportions. In so far as alterations have taken place the proportion of the

elements in the secondary rocks as compared with the original rocks is likely to be changed. For instance, alumina may be relatively increased in amount, and sodium greatly depleted, as compared with the potassium, etc., as explained on page 507 et seq. This process of alteration is likely to have proceeded far, in proportion as the material is fine grained. By increase in amount of decomposition and decrease in size of grains, the group of sands under consideration passes by gradation into the muds or pelites. By decrease of the ferromagnesian minerals they pass into the arkose sands. By decrease of the ferromagnesian and feldspathic minerals they pass into the quartz sands. Therefore there are all gradations between the ferromagnesian sands and the pelites, the quartz-feldspar sands, and the quartz sands.

GRITS.

In the belt of cementation, by consolidation, cementation, and metasomatism the ferromagnesian sands pass into grits. The grits occupy the same place in the family that sandstone and arkose bear in the quartz-sand and quartz-feldspar-sand families, respectively. In the induration of the grits consolidation by pressure and welding is comparatively unimportant. The principles of cementation applicable are identical with those of the sandstones and arkoses. A much greater number of cementing minerals are important in the grits than in either the sandstones or the arkoses. Where a ferromagnesian sand formation extends to the surface in the belt of weathering there may be contributed to the underground waters all the important elements which make up the great masses of the rocks. Also in the belt of cementation like diversified material may be added to the solutions by alteration of the minerals. Therefore, from the waters percolating through the ferromagnesian sands almost any of the common rock-making minerals which develop in the belt of cementation may be deposited. While this is true, the fact remains that the most abundant cement is quartz. Next in importance to this, in all probability, is calcite, and occupying a third place are the iron oxides. However, feldspar, hornblende, and other silicate minerals may be enlarged by each mineral selecting from the solutions appropriate materials for this purpose, precisely as with quartz. Also there may be deposited in the interstices such minerals as the zeolites, epidote, and chlorite, precisely as in the vacuoles of lavas, which have an equal variety of materials.

During cementation of the grits, metasomatism in the feldspars, ferromagnesian minerals, and constituents other than quartz is taking place. This process is precisely the same as in the metasomatism of the graywackes, next taken up; and since in these rocks the process is of greater consequence, it will not be here considered further than to remark that the expansion reactions which take place contribute material to the solutions for cementation.

It is believed that the change of the ferromagnesian sands to grits is mainly accomplished on the land areas. The argument is the same as with the graywackes. Since it can better be given after these rocks have been considered, the statement on this point is deferred. (See p. 882.)

Grits of Carboniferous age are rather extensive formations in various parts of the world. This is natural, since coal is known to have formed in lagoons and partly inclosed seas, and it has already been noted that such places, where the sorting power of the waves is small, are favorable ones for the building up of the ferromagnesian sands. But the grits are not by any means confined to the Carboniferous system; they occur extensively in the Cretaceous, Tertiary, and other systems.

GRAYWACKE.

Graywackes are produced from grits in the belt of cementation. Where the cementation is advanced so far that the rock when fractured breaks across the original grains rather than around them the rock is a graywacke. (Pl. X, *A*.) Graywacke, therefore, occupies the same position in the family under consideration that quartzite and completely indurated arkose occupy in the quartz-sand and quartz-feldspar-sand families. Nothing further need be said of the process of cementation, since it is mainly the completion of the work which cements a ferromagnesian sand into a grit. While the process of cementation is going on metasomatic changes may also be occurring in the body of the rock. (See Chapter VII, pp. 640–646.) The clastic particles may alter in many ways. To describe them in detail would be to give a treatment of the alteration of minerals. The final result of the alteration is a consolidated rock which may have a very great variety of mineral constituents. One of the most characteristic features of the graywackes is, however (as indicated by the name), their gray color. While the new minerals may have something of a tendency

to similar orientation, they usually do not become regularly parallel. The slight tendency toward a parallel arrangement usually accords with bedding, but in some cases it may not do so. The banded character of the original rock is ordinarily preserved, even if all of the decomposable detrital minerals are altered into new ones. Each mineral may change into any of the products which form in the belt of cementation, as listed. (See pp. 621–627.) To illustrate, the feldspars may alter into quartz, chlorite, the zeolites, and the epidotes; the pyroxenes and amphiboles may alter into quartz, serpentine, calcite, dolomite, magnesite, magnetite, and the epidotes; the micas may alter into serpentine, chlorite, and quartz. These secondary minerals vary from a subordinate to a dominant amount, and in some instances but little if any of the original feldspars, pyroxenes, amphiboles, and micas remain. But in general it is difficult to discriminate the metasomatic changes which take place in grits and graywackes from the partial alterations of the minerals before the material was deposited as a ferromagnesian sand. Where a ferromagnesian mineral of a certain kind is very abundant the alteration products from such a mineral are correspondingly plentiful.

Secondary minerals which form from several important primary minerals are likely to be especially abundant; as, for instance, serpentine. This mineral very often develops on a considerable scale in the graywackes. Indeed, it sometimes becomes so prominent that the metamorphism of graywackes has been called serpentinization. The secondary serpentine acts in a manner similar to that of silica. It may occupy the crevices and cracks, the spaces between the constituent minerals, and, finally, the place once taken by other minerals. Exactly as in the case of silica, material for the serpentine may be furnished in part or in whole by the minerals present, or the material of the serpentine may come from an extraneous source, especially from the belt of weathering. Widespread formations may be extensively serpentinized, so as to give for considerable areas almost solid masses of serpentine. The serpentinized graywackes are especially well illustrated in the Coast Range of California.[a] (Fig. 23.)

Excellent illustrations of the graywackes may be found in the Huronian of the Lake Superior region, and perhaps the best illustrations of all are

[a] Becker, G. F., Geology of the quicksilver deposits of the Pacific Slope: Mon. U. S. Geol. Survey, vol. 13, 1888, pp. 120–128.

the so-called slate-conglomerates of Logan in the Original Huronian area on the north shore of Lake Huron.[a] Here there are extensive formations the matrix of which is typical graywacke, and in which are scattered fragments, great and small, of the various rocks from which the finer débris was derived. By an increase in the amount and size of the coarse material, the graywackes pass into psephite-conglomerates. Almost equally good illustrations of graywackes are locally found in the great slate formation of the Penokee and Animikie series, although they are here not nearly so extensive as north of Lake Huron. Geikie describes graywacke as a rather common rock in Great Britain.[b]

The change from ferromagnesian sands to grits and graywackes is believed to take place in an important degree only when the deposits are below land areas. The argument in this connection is essentially the same as that applicable to the transformation of sands to sandstone and quartzite. The openings of the rocks are capillary, and it can not be presumed that in the rocks while below the water there is any rapid circulation by which material may be introduced. Indeed, there is no belt of weathering available which can furnish such material. But there is one difference between quartzose sand and the ferromagnesian sands. In the latter expansion reactions may occur while the rocks are below the water. So far as metasomatism there takes place, the processes of hydration, carbonation, and oxidation, all producing increase of volume, would provide material which could be deposited between the grains and thus cement the rocks. To what extent this process has actually taken place below the water must, for the present at least, be a matter of conjecture. But, as first stated, it is believed that the major part of the cementation and metasomatism of the graywackes occurred while the rocks were parts of land areas, for there the conditions are favorable for cementation, viz, vigorous circulation of the ground water and steady contribution of material to the belt of cementation from the belt of weathering.

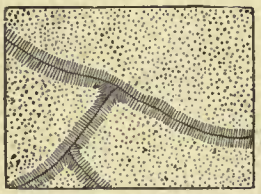


FIG. 23.—Graywacke undergoing serpentinization along cracks. After Becker.

After the graywackes have become cemented by deep burying they may pass into the zone of anamorphism. There metasomatic changes may take place in the rocks, in consequence of which the heavy

[a] Logan, W. E., Geology of Canada, 1863: Montreal, 1863, pp. 50–54.
[b] Geikie, Archibald, Text-book of geology: Macmillan & Co., London, 1893, p. 132.

minerals characteristic of that zone are formed. These minerals and their manner of development are, however, identical with those of the graywacke-schists and graywacke-gneisses next to be considered, and they will therefore not be here discussed.

SLATE-GRAYWACKE, SCHIST-GRAYWACKE, AND GNEISS-GRAYWACKE; OR GRAYWACKE-SLATE, GRAYWACKE-SCHIST, AND GRAYWACKE-GNEISS.

Where graywackes are buried deep enough to be in the zone of anamorphism and are subjected to mass-mechanical action, a schistose or banded rock is produced, to which the terms slate-graywacke, schist-graywacke, and gneiss-graywacke, or graywacke-slate, graywacke-schist, and graywacke-gneiss, are applicable. Where the movement is moderate the slate-graywackes or graywacke-slates are likely to form, but where the mass-mechanical movements are severe schists and gneisses develop.

The rearrangement of the minerals under mass-mechanical conditions combines the processes of recrystallization and granulation fully described in Chapter VIII (pp. 673–675, 690–696). The minerals which form are of course the heavy anhydrous minerals characteristic of the zone of anamorphism. The average composition of the minerals in a given case approximates that of the chemical composition of the original ferromagnesian sands, except so far as they have been changed in composition in the belt of anamorphism by dehydration and decarbonation or by injection.

Since one of the essential conditions for the formation of the ferromagnesian sands is disintegration with but little decomposition, within these rocks the various elements, including the alkalies and alkaline earths and iron, are likely to approximate the average original proportions of the rocks from which the sands were derived. It therefore follows that the ferromagnesian sands are likely to be richer in alkalies, alkaline earths, and iron than the quartz sands or even the quartz-feldspar sands. Since the rocks may contain nearly a full quota of all the elements, almost any of the minerals may form which are characteristic of the deep-seated zone, with the exception of the minerals rich in soda, such as sodalite, nephelite, etc., and the heavy aluminum silicate minerals. Apparently there has always been sufficient depletion in soda to prevent the development of the former. As pointed out on page 900, the latter are likely to develop only where there is an excess of aluminum beyond that required for the formation of the minerals containing the alkalies and alkaline earths.

The original quartz is granulated and recrystallized, as in the other varieties of sands. As the feldspars recrystallize, the micas are likely to form abundantly, especially biotite, since iron and magnesium are plentiful. (Pl. X, *B*.) But while the feldspar may in part pass into other minerals, it in large part recrystallizes as feldspar, with perhaps a change in species. Such new feldspar is apt to be an abundant constituent in the recrystallized rocks. Frequently the ferromagnesian minerals are so plentiful that the amphiboles develop extensively. In the abundance of amphibole these rocks differ from the schists and gneisses of the quartz-sand and quartz-feldspar-sand families. The particular amphibole which develops in a given formation depends, of course, upon the composition of the rock, but actinolite and common hornblende are very abundant. (Pl. X, *C* and *D*.) Rarely, where the metamorphism is of a very extreme nature, the pyroxenes may also develop to some extent, but any considerable quantity of these minerals is rather unusual. It is probable that the greater abundance of amphibole is due, in part at least, to the fact that in this group of minerals the ratio between the calcium and the magnesium is 1 : 1, whereas in the pyroxenes it is 3 : 1. So far as decomposition has taken place in the original sands, the calcium is likely to have been extracted in greater proportion than the magnesium (see pp. 515–516); therefore many of the ferromagnesian sands may have been so depleted in calcium that pyroxenes can not readily form. Associated with the more abundant minerals, the heavy metamorphic minerals, such as garnet, staurolite, and tourmaline, may appear. However, these minerals are not likely to form so abundantly as in the pelite family, and the aluminum-silicate group of minerals, so common in the pelites, is rarely found. So far as hydrous minerals have been produced in the belt of cementation, they are decomposed. The material of the chlorites may largely go into the micas, amphiboles, garnets, staurolite, and other minerals. The zeolites may pass into the feldspars, especially into albite or oligoclase. In short, any of the combinations of hydrous minerals which have been formed by the alteration of a heavy original mineral may recombine to reproduce the original heavy mineral; for instance, serpentine, gibbsite, and kaolin may unite to produce biotite; kaolin and quartz, or gibbsite and quartz, with sodium-bearing minerals, may unite to produce albite; serpentine and quartz to produce enstatite, etc.

The newly developed minerals show a marked tendency to similar dimensional arrangement. This tendency is very strongly marked with the micas, is important with the hornblendes, and applies to a considerable extent to quartz and the feldspars. Corresponding with the dimensional arrangement of the mica there is an eminent cleavage. There may be a cleavage corresponding to the dimensional arrangement of the hornblendes and the feldspars. This dimensional arrangement and mineral cleavage combined give the rocks a slaty or schistose structure, depending upon the coarseness of the mineral particles. (See pp. 778–779.)

Where the original ferromagnesian sands were banded in consequence of alternation of coarse and fine material, or of alternation of different combinations of the mineral constituents, this banding may be preserved and thus a gneissic structure be produced in the recrystallized rocks. Where there was a band in which quartz was very abundant, the laminæ are composed largely of quartz; where there was a quartz-feldspar band there is likely to be a lamina composed of quartz, feldspar, and mica; where there was a band in which were abundant ferromagnesian minerals there are likely to be laminæ in which hornblende, feldspar, mica, and quartz are all plentiful. Of course, the bands are not sharply separated from one another, and there is likely to be subordinate amounts of all the minerals which occur in the rock in each of the bands. The preservation of the banded structure is due to the fact, fully explained in Chapter VIII (pp. 764–766), that during the alterations which take place in the zone of anamorphism migration of large quantities of material does not take place for more than exceedingly short distances.

It will be seen later that the gneisses of igneous origin usually contain hornblende. The sedimentary gneisses belonging to the family under consideration usually contain hornblende, and therefore are more likely to be confused with the gneisses of igneous origin than with the gneisses of the quartz-sand or quartz-feldspar-sand families. (Pl. X, *C.*) However, in many cases the average chemical composition of the rocks and the arrangement and structures of minerals enable one to discriminate gneisses of the family here considered from those derived from the igneous rocks. But, apparently, where the sedimentary rocks are adjacent to great intrusive igneous masses of hornblende-granite the sedimentary rocks may

gain hornblende in consequence of the exomorphic effect, and in that way produce a graywacke-schist containing much hornblende and very similar to hornblendic-schists of igneous origin. (See Pl. X, *D.*)

The graywacke-slates, graywacke-schists, and graywacke-gneisses, of course, grade into the graywackes from which they are derived. Further, they grade on the one hand into the arkose-schists and arkose-gneisses, and on the other hand into the pelite-schists and pelite-gneisses.

PELITE ORDER.

MUD FAMILY.

Mud is the finest of the mechanical sediments. The greatest deposits of mud form at the mouths of large rivers. Where very great rivers empty into the sea deltas of immense thickness and size are built up of mud, as, for instance, the delta of the Mississippi. Great deposits of muds are also forming in the estuaries into which the rivers enter, such as the estuaries of the Atlantic. These delta and estuary deposits, besides being extensive, are of immense thickness. In mediterranean seas great deposits of mud may be built up as the products of many rivers. Thus Willis explains the Hamilton shale of the Devonian of the Appalachian region, a formation extending from New York to Maryland, and having a thickness of from 350 to 420 meters.[a] Also in the open sea, as a result of the process of sorting, the muds are carried beyond the psammites, and so extensive formations of mud of moderate thickness are built up.

Muds deposited in mediterranean seas or in the open ocean very frequently are interstratified with or grade into the psammites toward the shore. Seaward they frequently are interstratified, intermingled, or grade into the calcareous deposits. To a less extent similar transitions are found associated with delta and estuary deposits. Consequently we have deposits intermediate between muds and sandstones, and between muds and limestones. From the foregoing it follows that muds vary in composition from that of the various psammites to that of the carbonates. The rocks intermediate between the muds and the carbonates usually contain a large percentage of calcium, magnesium, and carbon dioxide.

On the average the material of which mud is composed has been

[a] Willis, Bailey, Paleozoic Appalachia, or the history of Maryland during Paleozoic time: Maryland Geol. Survey, vol. 4, pt. 1, 1900, pp. 57–61.

PLATE X

PLATE X.

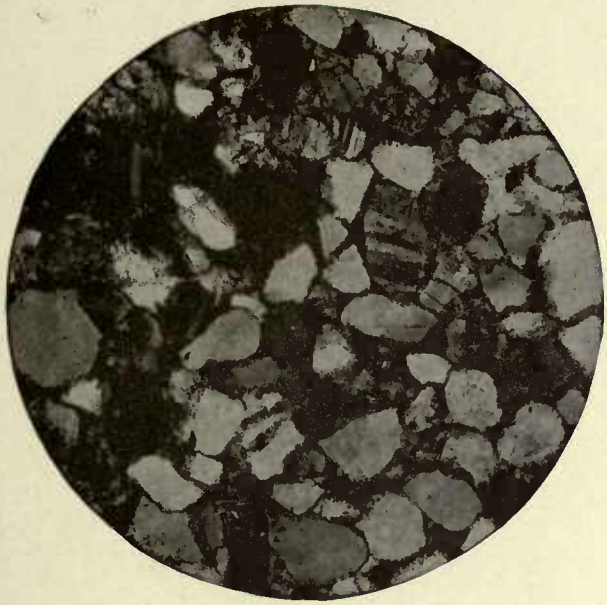
PHOTOMICROGRAPHS OF GRAYWACKES.

A. Graywacke from Penokee-Gogebic district of Michigan and Wisconsin. The orthoclase is in most cases separable from the quartz, in that it lacks the perfect clearness and uniformity of color which each grain of that mineral shows. The striated feldspars are nicely shown.

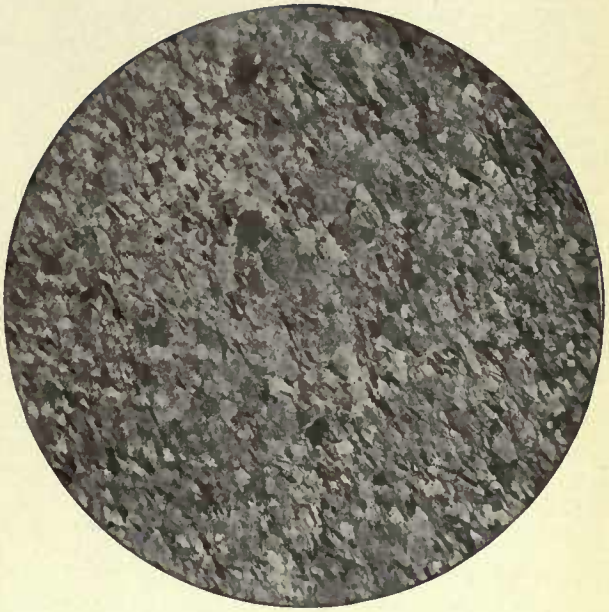
B. Biotite-graywacke from Mesabi district of Minnesota. This is the normal phase of Lower Huronian graywacke, consisting of quartz and feldspar grains, mainly the former, very imperfectly rounded, and a considerable amount of secondary biotite and muscovite or sericite. All the constituents have a dimensional parallelism, and the micas have also a crystallographic parallelism. After Leith.

C. The same, showing development of new hornblende near contact with intrusive granite. After Leith.

D. The same, showing development of new hornblende to the practical exclusion of mica at contact with intrusive granite. After Leith.



A



B

C

D

PHOTOMICROGRAPHS OF GRAYWACKES.

exposed to the weathering processes under more favorable circumstances than any other mechanical deposit. Consequently mud is material in which decomposition is farther advanced than in any of the previously considered classes of mechanical sediments. It follows from this that muds are likely to be deficient in the more readily soluble compounds. Of these the alkalies stand first, and of the alkalies sodium is more largely dissolved, since a large proportion of sodium in the original igneous rocks occurs in minerals which are more readily decomposed than the minerals which bear potassium—that is, sodium occurs largely in the nephelites, sodalites, and basic feldspars, which, as shown on pages 252, 260, 292, 295–299, are readily soluble; whereas the great sources of potassium are orthoclase and microcline, difficultly decomposable minerals. The materials are also apt to be depleted in calcium and magnesium, since the alkaline earths are so readily soluble. (See analyses A, B, C, of shales in Chapter XI, under "Composite analyses of sedimentary rocks." The depletion in calcium usually has gone farther than the depletion in magnesium, since in the belt of weathering much of the magnesia is retained in the serpentines and talcs. The material may or may not be depleted in iron. While aluminum and silica also have been dissolved in the belt of weathering, the solution of these substances is less rapid than of the others, and thus there is usually an increase in the relative amounts of these elements. The relative rate of solution of the elements is more fully considered on pages 507–518.

The processes which lead to the solution are those of carbonation, hydration, and oxidation, so frequently mentioned. From the muds the carbonates are mainly removed in solution, the hydroxides are removed to some extent, and the highly oxidized iron largely remains. All the foregoing facts clearly appear when the analyses of original igneous rocks are compared with those of muds. I reproduce from Clarke the first column of a table giving the average of analyses of igneous and crystalline rocks, made up from 830 analyses from various parts of the world, which may be regarded as closely approximating the composition of the original material from which the muds must have been derived, except that a considerable number of the 830 analyses are from metamorphic rocks, a portion of which may be metamorphic sedimentary rocks. So far as there was

depletion in any of the elements of such metamorphic sedimentary rocks, this would somewhat reduce the amount of these elements and correspondingly increase the amounts of the other elements.

Average of analyses of 830 igneous and crystalline rocks.[a]

	Per cent.		Per cent.
SiO_2	59.71	K_2O	02.80
Al_2O_3	15.41	H_2O	1.52
Fe_2O_3	2.63	TiO_2	.60
FeO	3.52	P_2O_5	.22
MgO	4.36	Total	99.22
CaO	4.90		
Na_2O	3.55		

Probably the best obtainable estimate of the composition of the muds is the average of analyses of 78 Cenozoic, Mesozoic, and Paleozoic shales given by Clarke. The individual shales are given weight proportional to the mass of the formation, as nearly as this could be done. His results, by combining the two composite analyses, one for 27 Mesozoic and Cenozoic shales and the other for 51 Paleozoic shales, are as follows:

Average of analyses of 78 shales.[b]

	Per cent.		Per cent.
SiO_2	58.38	P_2O_5	0.17
Al_2O_3	15.47	SO_3	.65
Fe_2O_3	4.03	Cl	.....
FeO	2.46	S	.....
MgO	2.45	MnO	Trace.
CaO	3.12	BaO	.05
Na_2O	1.31	SrO	None.
K_2O	3.25	Li_2O	Trace.
H_2O at 110°	1.34	Carbon (of organic origin)	.81
H_2O above 110°	3.68	Total	100.46
TiO_2	.65		
CO_2	2.64		

[a] Clarke, F. W., Analyses of rocks, laboratory of the U. S. Geol. Survey, 1880–1899: Bull. U. S. Geol. Survey No. 168, 1900, p. 14.

[b] Clarke, cit., Bull. 168, p. 17.

Probably the chief respect in which these shales differ in composition from muds is that water is less abundant in them. To compare the above analyses with the analyses of the original rocks, the water ought to be omitted. Omitting the water, and increasing the other elements in proportion, the analysis of shales would be as follows:

Analysis of shales on basis of 100 per cent excluding the water.

	Per cent.		Per cent.
SiO_2	61.45	SO_3	0.68
Al_2O_3	16.29	Cl	.....
Fe_2O_3	4.24	S	.....
FeO	2.59	MnO	Trace.
MgO	2.58	BaO	.052
CaO	3.29	SrO	None.
Na_2O	1.38	Li_2O	Trace.
K_2O	3.42	Carbon	.85
TiO_2	.68	Total	100.460
CO_2	2.78		
P_2O_5	.178		

For comparison there is inserted the average of 12 analyses of clays and soils from Illinois, Iowa, Minnesota, and Wisconsin.

Average of 12 analyses of clays and soils.[a]

	Per cent.		Per cent.
SiO_2	54.28	TiO_2	0.42
Al_2O_3	14.51	CO_2	3.53
Fe_2O_3	6.25	P_2O_5	.09
FeO	.77	SO_3	.08
MgO	2.99	Cl	.02
CaO	5.04	MnO	.08
Na_2O	1.21	Carbon, organic	.24
K_2O	2.12	Total	100.04
H_2O	8.41		

[a] Clarke, F. W., Analyses of rocks, laboratory of the U. S. Geol. Survey, 1880–1899: Bull. U. S. Geol. Survey No. 168, 1900, pp. 296–297.

The secondary minerals are important constituents of the muds. Of these the most abundant are those which especially form in the belt of weathering, as given on pages 518–521. With these there are, of course, almost all the minerals which form in the belt of cementation, as given on pages 621–627, and finally with both of these classes are residual unaltered minerals, especially refractory ones, such as quartz, orthoclase and microcline, albite, etc., and the heavy refractory minerals. Not infrequently the quartz and feldspar constitute the major portion of the material. From the foregoing it is clear that in proportion as alteration is advanced the minerals forming the muds tend toward the very end products of alteration—quartz, kaolin, talc, ferric oxide, and gibbsite. (See p. 520.) Some of the clayey muds are composed almost wholly of quartz and kaolin, with some talc and ferric oxide. It therefore appears that the muds have a wide variety of composition, both chemical and mineral.

SHALE FAMILY.

By consolidation, metasomatism, and cementation in the belt of cementation the muds pass into shales. Shale stands, in the pelite order, in the same place in which sandstone, arkose, and grit stand in the psammite order. The processes of alteration are the same in all, but their relative importance is very different in the pelites and psammites. In the induration of the psammites consolidation is of subordinate importance, and cementation by material derived from an outside source is of the first importance. In induration of the muds consolidation due to pressure is of the first importance. The particles are very small. According to Whitney, the finer soils, which in reference to subdivision may be taken as approximately the same as mud, contain from 10,000,000,000 to 20,000,000,000 particles per gram.[a] In a fine sand, such as the St. Peter sandstone of Wisconsin, the number of particles per gram, as determined by Mr. S. H. Ball, are about 115,000, and in a somewhat fine grained and better sorted beach sand about 167,000 particles per gram. Therefore in a mud, after the steady pressure has squeezed out the water so as to bring the particles in contact with one another, the number of points of contact are from 87,000 to 174,000 times as great as in such a sandstone as the St. Peter, and from 60,000 to 120,000

[a] Whitney, Milton, Some physical properties of soils in their relation to moisture and crop distribution:. U. S. Dept. Agric., Weather Bureau Bull. No. 4, 1892, pp. 73–74.

times as great as in the beach sand. Consequently, where the pressure is sufficient to bring the particles, or a fair proportion of them, so close together that they are within the limits of molecular attraction, welding is an important factor in the coherence of the rock. It is well known that when mud is subjected to very moderate pressure and the water can escape, this is sufficient to make the particles cohere. There is therefore every reason to believe that the weight of the superincumbent material accomplishes the same thing for mud formations.

Metasomatic processes are important in the induration of the muds. The mechanical water within the interstices of the muds and that liberated by dehydration are agents through which changes may be made within the mineral particles and between the adjacent mineral particles. That dehydration occurs is shown by comparison of the analyses of slates and shales with those of muds. It has been seen on pages 742–744 that the water of the slates and shales is, on the average, about 50 per cent of that of the muds.

Where rocks are so strongly hydrated as are the shales, some of the water is combined with the hydrous minerals which most readily part with it, such as the zeolites. Under such conditions the moderate pressures and temperatures which produce the shales are sufficient forces to begin dehydration.

Where organic matter is present in muds—and this is very common—the process of deoxidation is likely to begin. This is shown by the relative proportions of the ferric and ferrous oxides in the muds and shales, as exhibited in the analyses given on pages 890–891. It is seen that the ferric oxide in the clays and soils averages 6.25 per cent, and in the shales is reduced to 4.03 per cent; whereas the ferrous oxide in the clays and soils is 0.77 per cent and in the shales is increased to 2.46 per cent. These facts accord with the statement in Chapter IV (p. 165; also see Chapter VII, pp. 607–608) that deoxidation, while especially characteristic of the zone of anamorphism, takes place in the belt of cementation where the conditions are favorable. It thus appears that in the change from muds to shales we have the beginning of reactions which for most rocks are not important until they are deeply buried. Of the three reactions, hydration, oxidation, and carbonation, which are characteristic of the zone of katamorphism for the majority of rocks, two begin to be reversed for the pelites in the belt of

cementation. This simply means that the pelites begin to pass into the zone of anamorphism at less depth than do other rocks.

Cementation is of consequence for the pelites, but not of such dominant importance as in the psammites. The muds are practically impervious to percolating waters, because the openings between the particles are subcapillary. (See Chapter III, p. 143.) Hence very little material can be brought in from an outside source to fill the minute interspaces of the particles of mud; but by the metasomatic processes within the minute mineral particles the solutions obtain material which may be deposited between the grains. As the water is squeezed out by pressure, not only are the particles brought closer together, but as the water moves toward the place of escape the pressure lessens and material from solution is precipitated, and thus cements the particles. (See p. 114.)

The change of mud to shale is therefore largely a mechanical process of consolidation, resulting in welding; but the chemical processes of metasomatism and cementation also are important.

Where the shales pass into the zone of anamorphism and the conditions are mass-static, the processes of that zone are inaugurated. Dehydration may be carried far. The silication of the subordinate amounts of carbonates which are so generally present in the shales may take place. In the shales there is very frequently organic material, and this results in deoxidation. By metasomatism the heavy minerals develop. The rocks thus altered may become compact, strong rocks, composed of anhydrous minerals. The reactions for shales in the zone of anamorphism are those which produce the rocks next to be considered.

SLATE-PELITE, SCHIST-PELITE, AND GNEISS-PELITE; OR PELITE-SLATE, PELITE-SCHIST, AND PELITE-GNEISS.

Where shales are buried so deep as to pass into the zone of anamorphism and mass-mechanical action takes place, slate-pelites, schist-pelites, and gneiss-pelites, or pelite-slates, pelite-schists, and pelite-gneisses are produced. Where the depth is not great and the mass-mechanical action is not very severe slates are likely to form. Where the depth is greater and the mass-mechanical action is severe schists or gneisses are likely to develop. As the shales are very weak rocks, the depth at which the reactions of the zone of anamorphism are inaugurated is not great. It is certainly less, on the average, than for any of the previous families.

The rearrangement of the mineral particles under mass-mechanical conditions is mainly that of recrystallization. The process of granulation, which is so important in connection with recrystallization of the psephites and psammites, is of relatively less consequence in the deep-seated metamorphism of slate, although by no means unimportant. The particles of the original rocks are so small that they can readily slip over one another without being broken finer, so that granulation is mainly restricted to the large particles. The dominance of recrystallization is shown by the fact that the moment the change from shale to slate, schist, or gneiss commenced the small particles begin to merge and a coarser-grained rock is produced. (Pl. XI.)

The alterations which take place of course come under the general classes so frequently mentioned as characteristic of the zone of anamorphism—dehydration, silication, and deoxidation.

In order to get a better idea of the chemical change from mud to shale and then to slate and schist, analyses of slates and schists are here inserted. The average of 12 analyses of clays and soils is given on page 891. The average of composite analyses of 78 shales is given on page 890. The following is an average of the analyses of 9 slates from Vermont:

Average of analyses of 9 slates from Vermont.[a]

	Per cent.		Per cent.
SiO_2	61.25	TiO_2	0.83
Al_2O_3	16.61	CO_2	.82
Fe_2O_3	2.01	P_2O_5	.12
FeO	4.83	MnO	.14
MgO	2.80	BaO	.06
CaO	.83	FeS_2	.22
Na_2O	1.42	Carbon	.05
K_2O	4.24	Total	100.07
H_2O at 100°	.27		
H_2O above 100°	3.57		

The following is the average of 22 analyses of pelite-slates from various localities in the United States, taken from the publications of

[a] Clarke, F. W., and Hillebrand, W. F., Analyses of rocks and analytical methods, U. S. Geol. Survey, 1880–1896: Bull. U. S. Geol. Survey No. 148, 1897, pp. 277–278.

the United States Geological Survey. Analyses were taken only from specimens which were clearly of pelitic origin.

Average of analyses of 22 pelite-slates.

	Per cent.		Per cent.
SiO_2	61.90	P_2O_5	0.044
Al_2O_3	16.538	SO_3	.025
Fe_2O_3	2.726	Cl	Trace.
FeO	3.634	F	Trace.
MgO	2.988	S	None.
CaO	1.066	MnO	Trace.
Na_2O	2.566	BaO	.01
K_2O	3.146	SrO	Trace.
H_2O at 110°	.533	Li_2O	Trace.
H_2O above 110°	3.311	FeS_2	.112
TiO_2	.82	C	.222
CO_2	.590	Total	100.231

The following is the average of 5 analyses of pelite-schists from various localities in the United States, taken from the publications of the United States Geological Survey. Analyses were taken only from specimens which were clearly of pelitic origin.

Average of analyses of 5 pelite-schists.

	Per cent.		Per cent.
SiO_2	65.740	P_2O_5	0.122
Al_2O_3	17.348	SO_3	.032
Fe_2O_3	1.896	Cl	Trace.
FeO	3.348	F	.068
MgO	1.896	S	.....
CaO	1.252	MnO	.034
Na_2O	1.784	BaO	.046
K_2O	3.280	SrO	Trace.
H_2O at 110°	.195	Li_2O	Trace.
H_2O above 110°	1.815	C	.582
TiO_2	.554	Total	99.992
CO_2	None.		

By comparing the analyses of the shales, slates, and schists it is seen that the chief chemical changes are those of loss of water and of carbon dioxide, and transformation of the ferric iron to the ferrous form. The first of these changes is evidence of the process of dehydration, so characteristic of the zone of anamorphism. It is notable, as pointed out in Chapter VIII (p. 744), that in the change from clays and soils, which certainly do not contain more water than muds, to shales and slates the combined water is reduced by one-half, and that in the further transformation to schists the combined water is again reduced by one-half or one-third. The disappearance of the carbon dioxide of the carbonates is due, of course, to the process of silication, the silica uniting with the bases of the carbonates and forming silicates, and the carbon dioxide slowly escaping with the squeezed-out water. It has already been noted that deoxidation begins in the change from muds to shales. The average amount of ferric iron is further decreased as the process of metamorphism goes on, as shown by the fact that in the shales the ferric oxide is 4.03 per cent, in the slates is 2.726 per cent, and in the schists is 1.896 per cent. Correlative with this process is increase of ferrous oxide from 2.46 per cent in the shales to 3.634 per cent in the slates and 3.348 per cent in the schists. (See pp. 890, 896.) In the analyses of shales from eight different States, given in the publications of the United States Geological Survey, carbon is reported in six of them. The carbon in the shales is an adequate reducing agent for this work. While the amount of carbon in the shales is not great, it is persistently present. The average amount of carbon in 78 shales is 0.81 per cent.[a] (See p. 890.) It is to be remembered that this amount of carbon is much more than sufficient to reduce all of the ferric iron to the ferrous state, as is shown by the following equation:

$$2\,Fe_2O_3 + C = 4\,FeO + CO_2.$$

Since the molecular weight of two molecules of Fe_2O_3 is 320, and the atomic weight of carbon is 12, this equation means that 12 parts of carbon is theoretically sufficient to reduce 320 parts of the ferric oxide to ferrous oxide. It follows, therefore, that 0.81 per cent of carbon would theoretically reduce 20 per cent of ferric iron to the ferrous state. Since the total

[a] Clarke, F. W., Analyses of rocks, laboratory of the U. S. Geol. Survey, 1880–1899: Bull. U. S. Geol. Survey No. 168, 1900, p. 17, col. C.

amount of ferric oxide is 6.25 per cent in clays and soils and 4.03 per cent in the shales,[a] it is clear that the small amount of carbon in the shales furnishes, by its reducing action, an entirely adequate cause for the partial change of the ferric to ferrous iron as metamorphism of the pelites continues from muds to shales, slates, schists, and gneisses.

The fact that, with the exceptions of the chemical changes mentioned, the compositions of the pelitic gneisses, schists, and slates, where unmodified by igneous intrusions, correspond with those of the shales and muds is positive evidence of the general conclusion given on pages 145, 764–766, that circulating ground waters are unable to transport material from an outside source through rocks the particles of which are so small as to furnish only subcapillary openings. Of this principle the pelite family affords the best illustration.

The development of the minerals will first be considered at the stage where the rocks are slates, and second where they have been transformed to schists or gneisses.

Development of minerals of slates.—Out of the constituents which are present in the irresolvable background of the shales, innumerable flakes of mica and small particles of quartz develop. The feldspar, with the addition of other constituents, also largely alters into quartz and mica. (Pl. XI, *A*.) From a single fragmental grain of feldspar are produced many individuals of interlocking quartz and mica. (Pl. XI, *B*.) The minerals formed in the interstices interlock with one another and with those produced from the feldspar grains, so that an approximately uniform interlocking groundmass of quartz and mica is produced. If fragmental grains of quartz are not present to indicate the clastic character of the rock, the secondary interlocking quartz and mica do not betray this. The most abundant mica is usually biotite. Frequently muscovite accompanies the biotite. The sources of the material for the micas of the slates are the same as for the micas of the schists and gneisses. (See pp. 899–900.)

While in the ordinary slates the process of recrystallization as above described is inaugurated, it is far from complete, and many of the original mineral particles of the mud usually remain partly changed or wholly unchanged.

---

[a] Clarke, cit., Bull. 168, p. 17, col. C.

Development of minerals of schists and gneisses.—The processes which result in the formation of pelite-slate from shale when carried to completion produce pelite-schist (Pl. XI, *C*) or pelite-gneiss. All stages of the change may be seen. We see, besides the replacement of the feldspar by quartz and mica, the granulation and recrystallization of the quartz and the feldspar. The process is essentially the same as the development of slate, except that the destruction of the clastic quartz and feldspar grains is greatly promoted by mashing. The process takes place in perfection in proportion as the rock is fine grained. Thus a shale may completely change to pelite-schist, while an interbedded coarse-grained grit may still reveal evidence of its fragmental origin. In the same way a conglomerate may have its matrix completely changed to a schist and the resistant pebbles be merely deformed; but in the case of extreme alteration the most resistant and largest pebbles and bowlders are entirely destroyed. (See pp. 858–859.)

In the typical schist-pelites and gneiss-pelites the chief minerals present are quartz, muscovite, and biotite. (Pl. XI, *C*.) This is a natural consequence of the composition of the shales. The orthoclase and microcline feldspars, with the probable addition of alumina from the background, in most cases recombine into quartz and muscovite. (See pp. 254–255.) This uses up much of the potassa, alumina, and silica. Where magnesium and iron are also available biotite is formed. (See p. 255.) Usually some residual feldspar remains or is produced by recrystallization, and the amount of this material is likely to be great in proportion as soda was present in undecomposed plagioclase.

Since silica and alumina are abundant, an acid plagioclase is most likely to form. Consequently albite is the most frequent plagioclase of the schist-pelites and gneiss-pelites. If the amount of soda be considerable, the albite may be so abundant as to be a chief constituent. Such an albite-pelite-gneiss is beautifully illustrated by the Hoosac formation of Hoosac Mountain, Massachusetts, described by Wolff.[a] (Pl. XI, *D*.) In some cases where the soda is unusually plentiful, a part of the soda with alumina may pass into the soda-mica paragonite. Indeed, soda may more frequently go into paragonite in the schist-pelites and gneiss-pelites than has been supposed, for the close microscopical and chemical examinations of recent

[a] Pumpelly, Raphael, Wolff, J. E., and Dale, T. Nelson, Geology of the Green Mountains in Massachusetts: Mon. U. S. Geol. Survey, vol. 23, 1894, pp. 59–64.

years have shown that the sericite of many of the so-called sericite-schists is probably paragonite rather than muscovite; but the paragonite-schists in many cases are not pelite-schists, but are derived from the alteration of igneous rocks. As already seen, analyses of original muds show that, on the average, the potassa is several times more abundant than soda, and this fact explains why muscovite is so much more common in the slate-pelites, schist-pelites, and gneiss-pelites than is paragonite.

While the greater part of the potassium probably passes into muscovite, where the potassa is abundant a portion of it in many cases undoubtedly passes into feldspar, producing orthoclase and microcline, since these minerals are rather abundant in many of the schist-pelites and gneiss-pelites. All the important elements which go to make up the muds are fully accounted for in the minerals quartz, biotite, muscovite, paragonite, albite, orthoclase, and microcline.

Where there is an excess of alumina beyond that required for the formation of the minerals already mentioned, since silica is always in excess, aluminum-silicate minerals form, and thus is produced the andalusite-sillimanite-cyanite series. The development of these minerals accounts for a part of the material of the kaolin, which by dehydration and separation of silica may pass directly into any of the aluminum-silicate minerals, according to the reaction:

$$H_4Al_2Si_2O_9 = Al_2SiO_5 + SiO_2 + 2H_2O,$$

with a decrease in volume of the quartz and aluminum-silicate mineral of from 25.40 to 26.28 to 31.61 per cent, depending upon whether andalusite, sillimanite, or cyanite, respectively, be formed. Ordinarily the andalusite, having the lowest specific gravity, forms when the metamorphism is moderate, as in the slates. Sillimanite, having a higher specific gravity, is likely to form where the metamorphism is more intense; and where the metamorphism is most intense the heaviest of the aluminum-silicate minerals, cyanite, may develop. This fully conforms to the principle explained on pages 363–365, 683–685, that in proportion as a rock is deeply buried and metamorphism is profound, minerals of high specific gravity form. These three minerals in the inverse order mentioned are described by Emerson as occurring peripherally to great batholiths of granite in western Massachusetts. (See pp. 717–718.)

PLATE XI

PLATE XI.

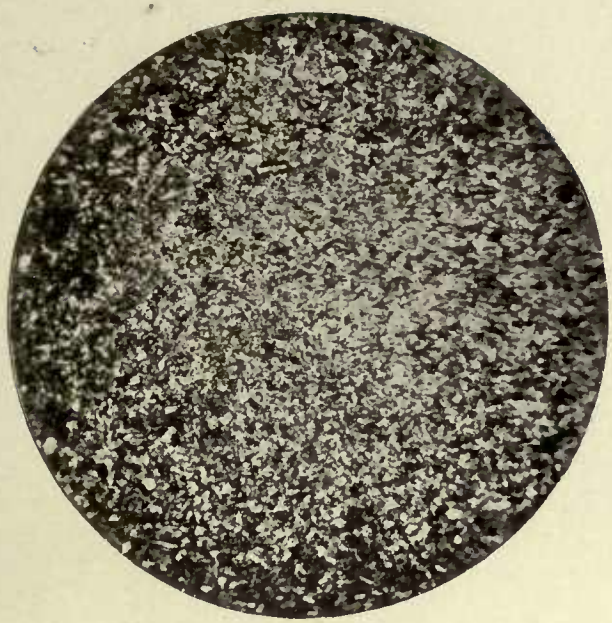
PHOTOMICROGRAPHS OF PELITES.

A. Slate from Mesabi district of Minnesota. This is the normal, fine-grained Virginia slate, consisting of quartz and feldspar, chlorite, muscovite, biotite, and iron oxide, all the constituents arranged with their longer diameters roughly parallel, though the chlorite and iron oxide are arranged to a less extent than the other constituents. After Leith.

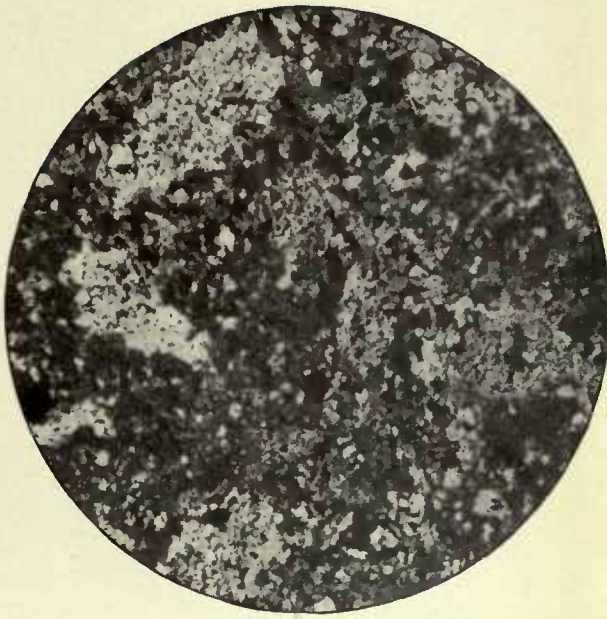
B. Biotite-slate from Penokee-Gogebic district of Michigan and Wisconsin. Shows the alteration of the feldspars to the micas. The crystalline character of the developing rock is well shown. There remain, however, areas of feldspar which act as a unit, although they are cut in every direction by the alteration products, quartz and mica.

C. Muscovite-biotite-quartz-schist, showing uniformity of texture. Black Hills, South Dakota.

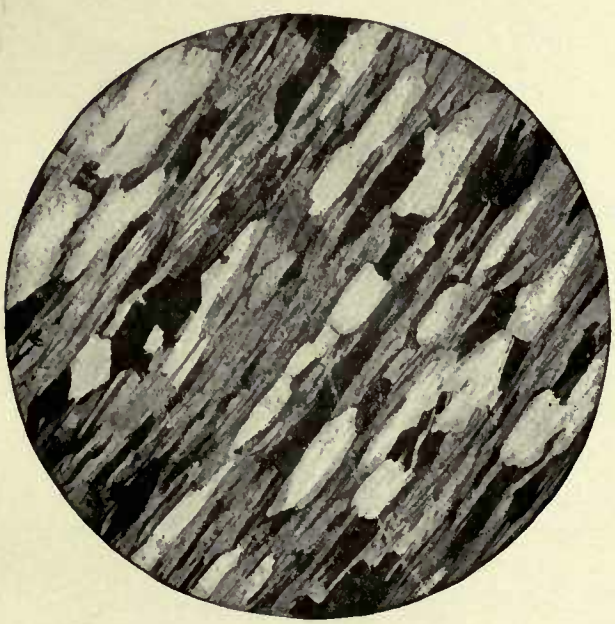
D. Albite-gneiss from Hoosac Mountain, Massachusetts. Shows no trace of clastic origin. After Wolff.



A



B



C

D

PHOTOMICROGRAPHS OF PELITES.

Simultaneously with the development of the aluminum-silicate series, garnets and staurolites may be produced. The garnet usually marks a stage of alteration less advanced than the staurolite, and thus it is that very often schist-pelites and gneiss-pelites are garnetiferous and not staurolitic, but in almost every case staurolitic schists and gneisses are garnetiferous. The development of the garnets may use parts of any of the constituents, calcium, magnesium, aluminum, iron, depending on the kind of garnet. Common garnet, as explained in Chapter V (p. 302), is usually an isomorphous mixture of grossularite, pyrope, and almandite, and occasionally melanite. The particular garnet which develops in a given case largely depends upon the elements which are present in the original rock. In case iron is rather plentiful and the metamorphism is intense, staurolite is also likely to form. The development of these minerals disposes of a large amount of iron and alumina, iron being derived from the oxide, and alumina in many cases being derived from the kaolin or from gibbsite or diaspore. If exceptional elements are present, as, for instance, boracic acid, tourmaline and other exceptional minerals may form.

While in the majority of the schist-pelites and gneiss-pelites feldspar is rather subordinate, in certain of them, as already noted, it is plentiful. In proportion as the feldspar becomes abundant, the material from which the rock was derived grades toward the quartz-feldspar-sand family of the psammite order.

During the metamorphism of the shales to slates, schists, and gneisses the new mineral particles which develop have a very strong tendency to dimensional arrangement. Indeed, the pelite order is the one which shows this dimensional arrangement to the best advantage. The rocks here belonging are the types of rocks of this class. The mineral of most fundamental importance showing the dimensional arrangement is, of course, mica, although some of the other minerals which develop show a marked dimensional arrangement. That the eminent cleavage of mica corresponds with its dimensional arrangement has been frequently mentioned heretofore, and is dealt with in detail by Leith.[a] Consequent upon the correspondence of the dimensional arrangement and cleavage of the newly crystallized mica, the eminent cleavage of the slates, schists, and

[a] Leith, C. K., Rock cleavage.

gneisses of the pelite order results, thus affording the best examples of rock cleavage.

Where the shales are rather homogeneous in texture, slates and schists form. Where, however, the original muds had alternations of coarse and fine material, or alternations of bands of material of different chemical compositions, these differences are apt to be maintained, to some extent at least, in the metamorphosed rocks, and thus a banded gneissic structure be produced. Each band of such a gneiss corresponds approximately in chemical composition to that of the original rock, and is mainly composed of the particular minerals, in the approximate proportions, which may be produced from the band of mud.

Since the muds are the most extensive of mechanical sediments, it naturally follows that there are great formations composed of their metamorphosed equivalents—slate-pelites, schist-pelites, and gneiss-pelites. As illustrations of coarse pelite-schists having a very widespread occurrence may be mentioned the Hudson schists of New England and New York, of Silurian age.[a] Other equally good illustrations of very extensive schist-pelite formations are those of the Upper Huronian formation of the Lake Superior region.[b] Many other illustrations might be mentioned, but it is hardly necessary to take the space to do this.

IGNEOUS ROCKS.

As yet we have no classification of the igneous rocks to which there is general agreement. In this respect the igneous rocks stand on a basis different from that of the sediments. As no classification of the igneous rocks is agreed upon, since petrographers themselves have not decided as to which rocks shall have specific names, and as it is agreed that there are

[a] Merrill, F. J. H., Metamorphic crystalline rocks in New York City district: Geologic Atlas U. S., folio 83, U. S. Geol. Survey, 1902, p. 4.

[b] Irving, R. D., and Van Hise, C. R., The Penokee iron-bearing series of Michigan and Wisconsin: Mon. U. S. Geol. Survey, vol. 19, 1892, pp. 296–345. Van Hise, C. R., and Bayley, W. S., with H. L. Smyth, The Marquette iron-bearing district of Michigan: Mon. U. S. Geol. Survey, vol. 28, 1897, pp. 444–459. Clements, J. Morgan, and Smyth, H. L., with W. S. Bayley and C. R. Van Hise, The Crystal Falls iron-bearing district of Michigan: Mon. U. S. Geol. Survey, vol. 36, 1899, pp. 164–174. Bayley, W. S., The Menominee iron-bearing district of Michigan: Mon. U. S. Geol. Survey, vol. 46, 1903, pp. 320–321, 462–488. Leith, C. K., The Mesabi iron-bearing district of Minnesota: Mon. U. S. Geol. Survey, vol. 43, 1903, pp. 168–177. Clements, J. Morgan, The Vermilion iron-bearing district of Minnesota: Mon. U. S. Geol. Survey, vol. 45, 1903, pp. 391–396.

gradations between many kinds of rocks to which names have been assigned, it is evident that it is impossible at the present time to trace out the stages of alteration of the various rock species. All that is now possible is to indicate how metamorphic igneous rocks may be handled in order to lead at some future time to a systematic treatment similar to that applied in the present treatise to the sedimentary rocks.

A series of names has been proposed (pp. 776–784) to designate the different kinds of alterations to which rocks are subjected, and their usage pointed out. But it seems desirable here to apply these usages to the igneous rocks, even at the risk of repetition. If it is desirable only to express the general fact of alteration, without indicating its character, the term "*meta*" is prefixed. If the alterations have taken place under mass-static conditions, so that textures and structures are preserved, the term "*apo*" is prefixed. If the alterations have taken place under mass-mechanical conditions, so that a slaty, schistose, or gneissose structure is produced, the terms schistic or gneissic may be prefixed. If it is desired to emphasize the structure rather than the kind of rock, the name of the rock may be placed before the structural name, as gabbro-schist. Finally, the dominant metamorphic minerals not implied by the name of the rock may be prefixed, as, for instance, chlorite meta-dolerite. Another illustration is hornblende-dolerite. This is the proper name for rocks which were originally dolerite but in which the pyroxene has changed to amphibole. Such rocks occur extensively in the Lake Superior region, where they have been generally called diorite. But they do not ordinarily have the same chemical composition as the diorites, in which the hornblende is original, nor is the feldspar usually the same. If accompanying the alteration a secondary structure is produced, the altered dolerite may become hornblende-schist-dolerite or hornblende-dolerite-schist.

Each of the igneous rocks has a certain range in chemical composition and is composed of certain important minerals. The alterations to which the constituent minerals of rocks are subject in the zones of katamorphism and anamorphism and in the belts of weathering and cementation of the former zone have been fully given (see Chapter V), and the variations in the alterations in each of these zones and belts have been fully discussed. (Chapters IV, VI, VII, and VIII.) Supposing the zone and conditions to

be definite for a given rock, one can specify what alterations are likely to occur, so far as each mineral is concerned, and also the alterations which are likely to take place from a particular combination of minerals. It is believed that this information will be of great service in a future systematic study of the metamorphism of the various igneous rocks in the different belts and zones of metamorphism, for it is a great advantage to have definite suggestions as to what may occur. Such suggestions in effect ask the question, when one is making observations, whether or not the facts of alteration for each rock in the different zones and belts correspond to the expectation. If they do the suggestions are confirmed, if not, advance has still been made upon the problem as to the physical conditions under which the alterations observed actually took place.

Once a fair degree of agreement is reached as to the orders, families, and species of the original igneous rocks, it will be possible to trace out their alterations in the various zones and belts in a manner somewhat similar to that in which the alterations of the sedimentary rocks have been imperfectly traced out. This, however, is plainly a work which will not be accomplished for many years. In the meantime this chapter furnishes guideboards telling how a great territory of petrography, only peered into from the borders, may be occupied.

Rec'd UCB EART
JUL 18 1986

RETURN TO → EARTH SCIENCES LIBRARY
230 Earth Sciences Bldg. 642-2997
0235

LOAN PERIOD 1	2	3
7 DAYS	1 MONTH	
4	5	6

ALL BOOKS MAY BE RECALLED AFTER 7 DAYS
Books needed for class reserve are subject to immediate recall

DUE AS STAMPED BELOW

FORM NO. DD8
UNIVERSITY OF CALIFORNIA, BERKELEY
BERKELEY, CA 94720

-345

GENERAL LIBRARY - U.C. BERKELEY

B000157873

SAN FRANCISCO
TRADE BINDERY
Complete Bindery Service
Phone YUkon 6-2887